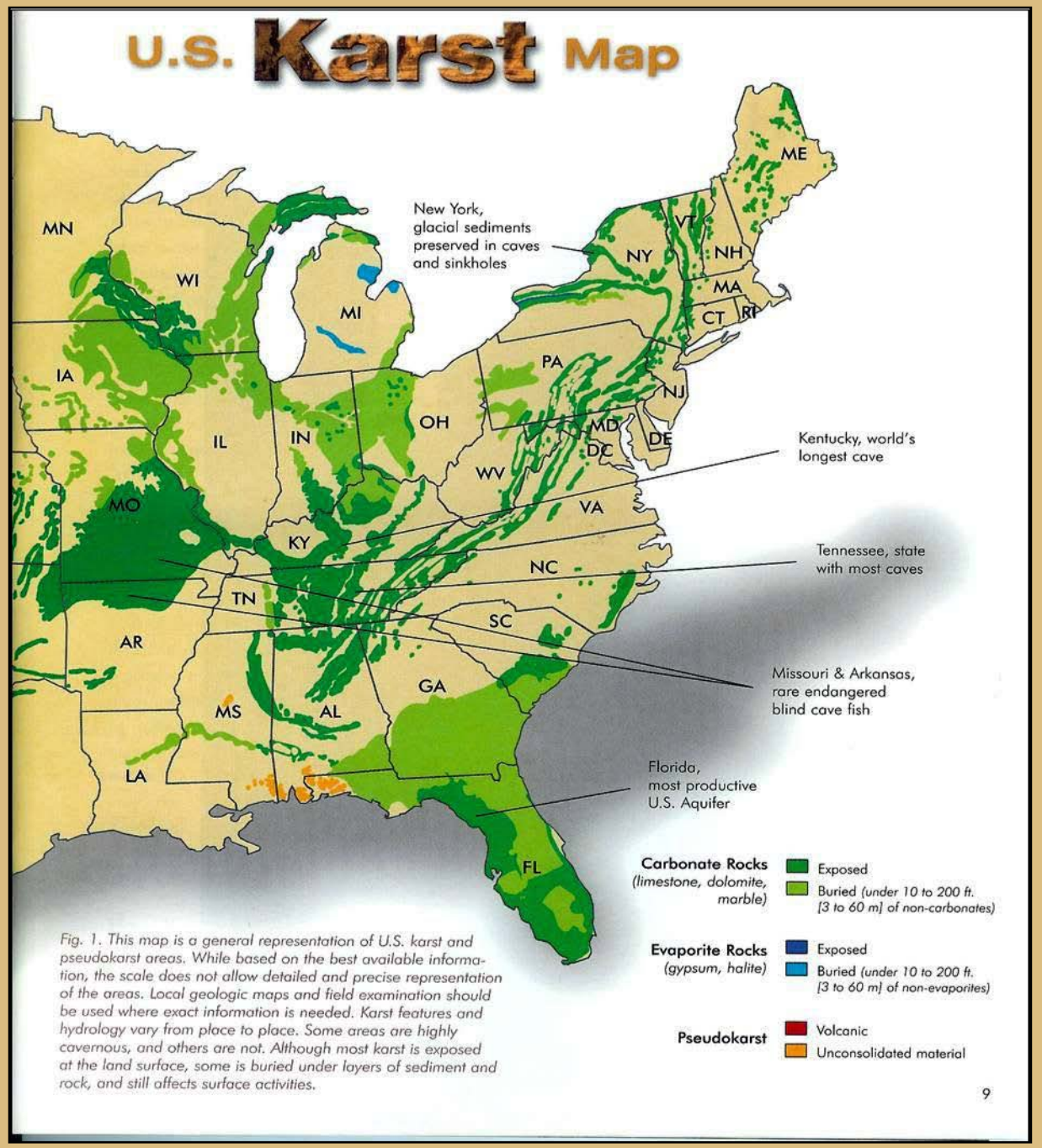
Dye Tracer Tests in Karst

- *Nicholas C. Crawford, Ph.D., P.G.*

Center for Cave and Karst Studies
Applied Research and Technology Program of Distinction
Department of Geography and Geology
Western Kentucky University
Bowling Green, KY 42101



Map showing karst areas east of Oklahoma.

Source: *Living With Karst* by Veni, DuChene, Crawford, Groves, Huppert, Kastning, Olson, and Wheeler.

- Do dye tracer tests using activated coconut charcoal packets with elutant analysis on a spectrofluorophotometer provide definitive results?

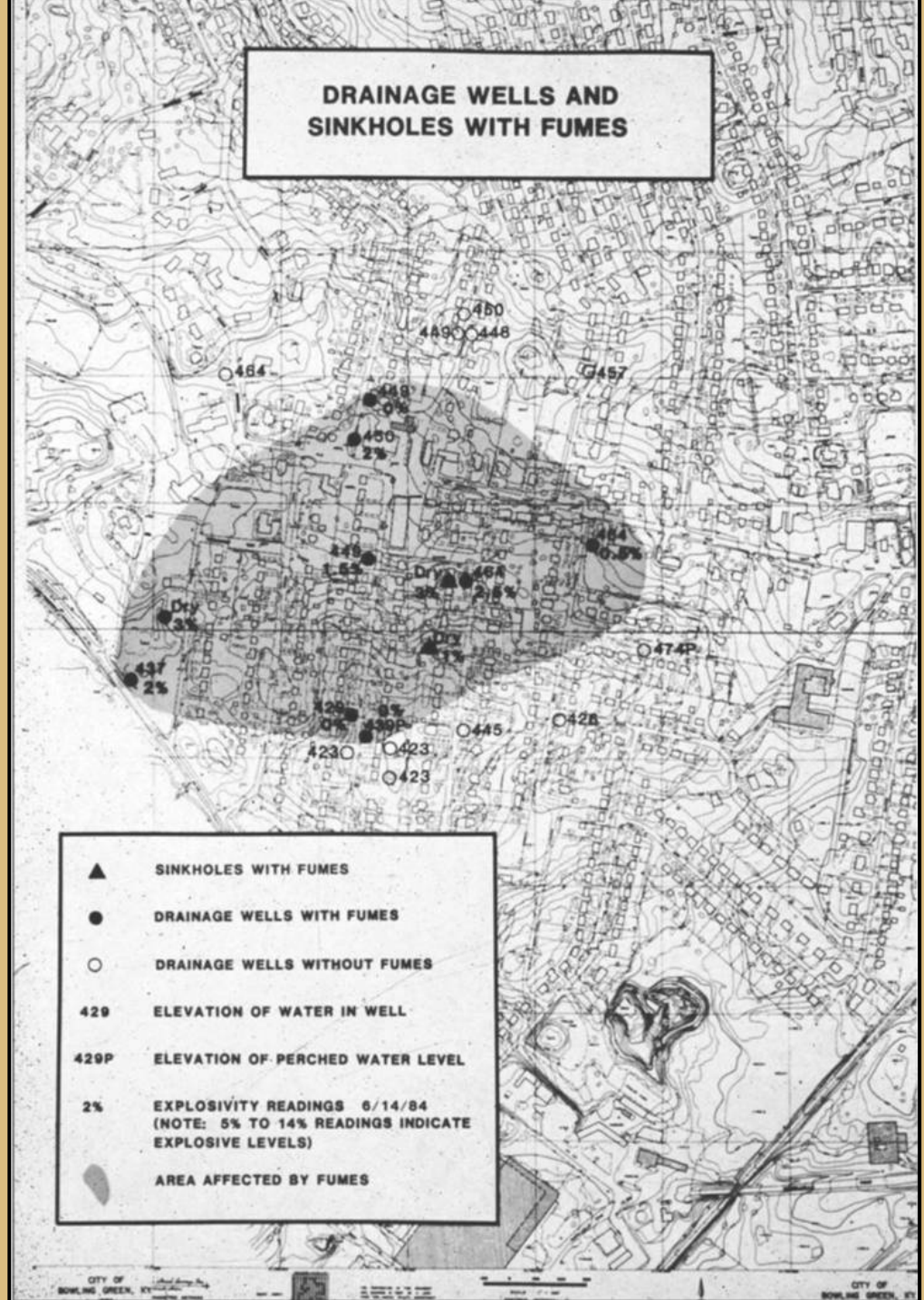
- Answer: YES, if performed by scientists knowledgeable about karst hydrogeology and dye tracer techniques.

- Problems associated with the storage and transportation of hazardous liquids upon karst

Bowling Green, Kentucky:

- Superfund Emergency 1985-1986

Toxic and explosive vapors rising from storm water drainage well.
USEPA Superfund emergency Bowling Green, 1985-1986


DRAINAGE WELLS AND
SINKHOLES WITH FUMES
450
449
448
464
457
448
0%
450
2%
464
0.8%
445
1.5%
Dry
3%
464
2.5%
Dry
3%
Dry
3%
474P
437
2%
428
0%
430P
8%
445
428
423
423
423
SINKHOLES WITH FUMES
DRAINAGE WELLS WITH FUMES
DRAINAGE WELLS WITHOUT FUMES
429 ELEVATION OF WATER IN WELL
429P ELEVATION OF PERCHED WATER LEVEL
2% EXPLOSIVITY READINGS 6/14/84
(NOTE: 5% TO 14% READINGS INDICATE
EXPLOSIVE LEVELS)
AREA AFFECTED BY FUMES
CITY OF
BOWLING GREEN, KY
CITY OF
BOWLING GREEN, KY

Health investigation by USEPA and the US Centers for Disease Control of toxic and explosive vapors rising from the karst aquifer into peoples' homes. Investigation lasted 8 months. 1985-1986

Toxic and explosive vapors rise into Parker Bennett Elementary School in Bowling Green, Kentucky on Thanksgiving weekend in 1985. Excavation to bedrock revealed that the vapors were rising from a bedrock crevice.

Pipe with large explosive proof fan used to vent vapors into the atmosphere at Parker-Bennett school.

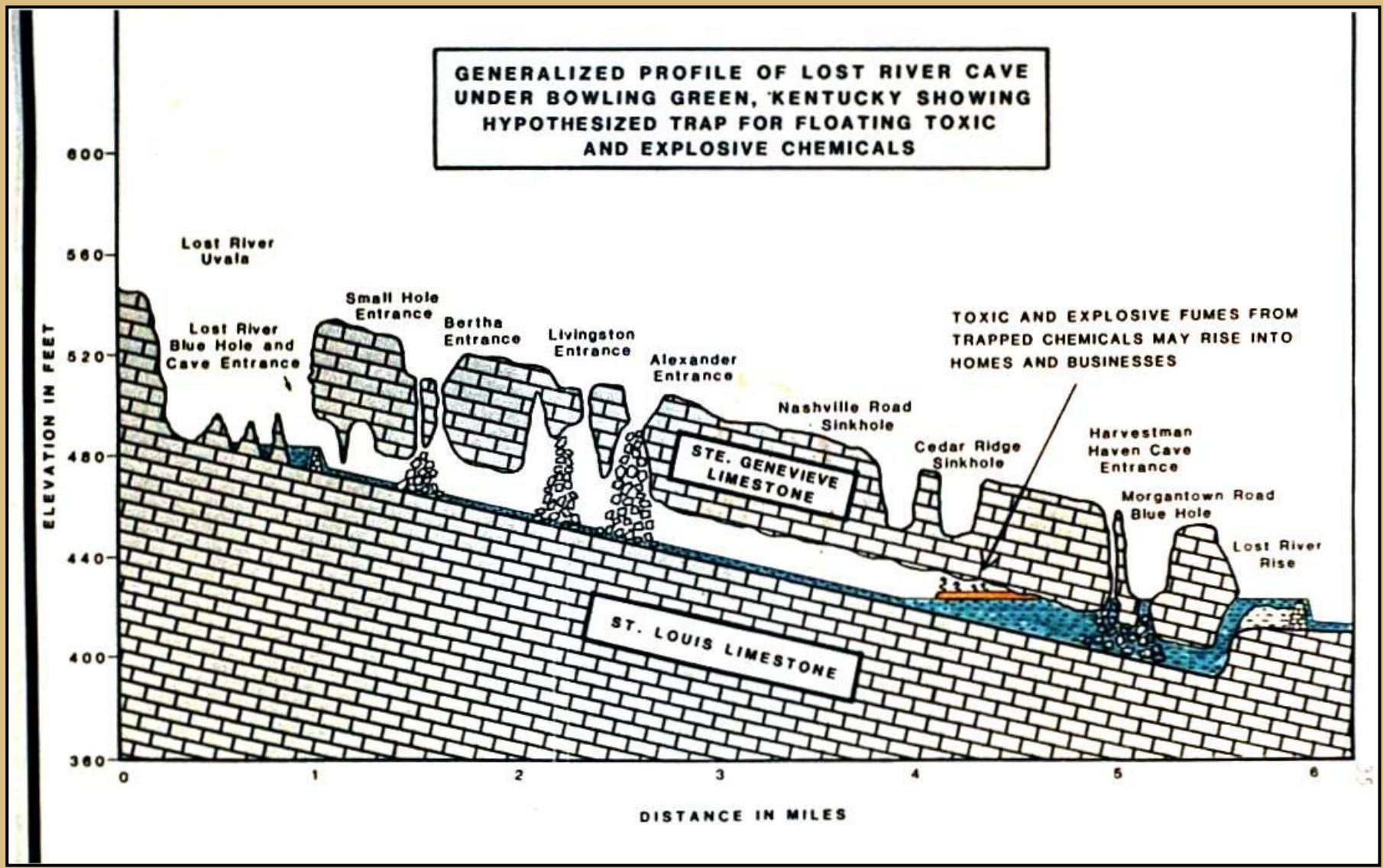
Excavation to expose crevice at Dishman-McGinnis Elementary School in Bowling Green, Kentucky.

Bedrock crevice at Dishman-McGinnis school.

Pipe and fan to vent toxic and explosive vapors into the atmosphere at Dishman-McGinnis Elementary School.

Ventilation pipe and fan at George Diamond’s home is typical of ventilation systems at other houses.

Excavation by the Center for Cave and Karst Studies into storm water drainage well leading into Napier Cave. Notice trap for storm water in foreground and vapor ventilation fan adjacent to house in background.


GENERALIZED PROFILE OF LOST RIVER CAVE UNDER BOWLING GREEN, KENTUCKY SHOWING HYPOTHESIZED TRAP FOR FLOATING TOXIC AND EXPLOSIVE CHEMICALS
ELEVATION IN FEET
600
560
520
480
440
400
360
Lost River Uvala
Lost River Blue Hole and Cave Entrance
Small Hole Entrance
Bertha Entrance
Livingston Entrance
Alexander Entrance
Nashville Road Sinkhole
Cedar Ridge Sinkhole
Harvestman Haven Cave Entrance
Morgantown Road Blue Hole
Lost River Rise
TOXIC AND EXPLOSIVE FUMES FROM TRAPPED CHEMICALS MAY RISE INTO HOMES AND BUSINESSES
STE. GENEVIEVE LIMESTONE
ST. LOUIS LIMESTONE
0
1
2
3
4
5
6
DISTANCE IN MILES

Drums of toxic waste were stored near a truck dock loading ramp that drained directly into a bedrock crevice.

Dye trace of truck dock loading ramp drainage crevice.

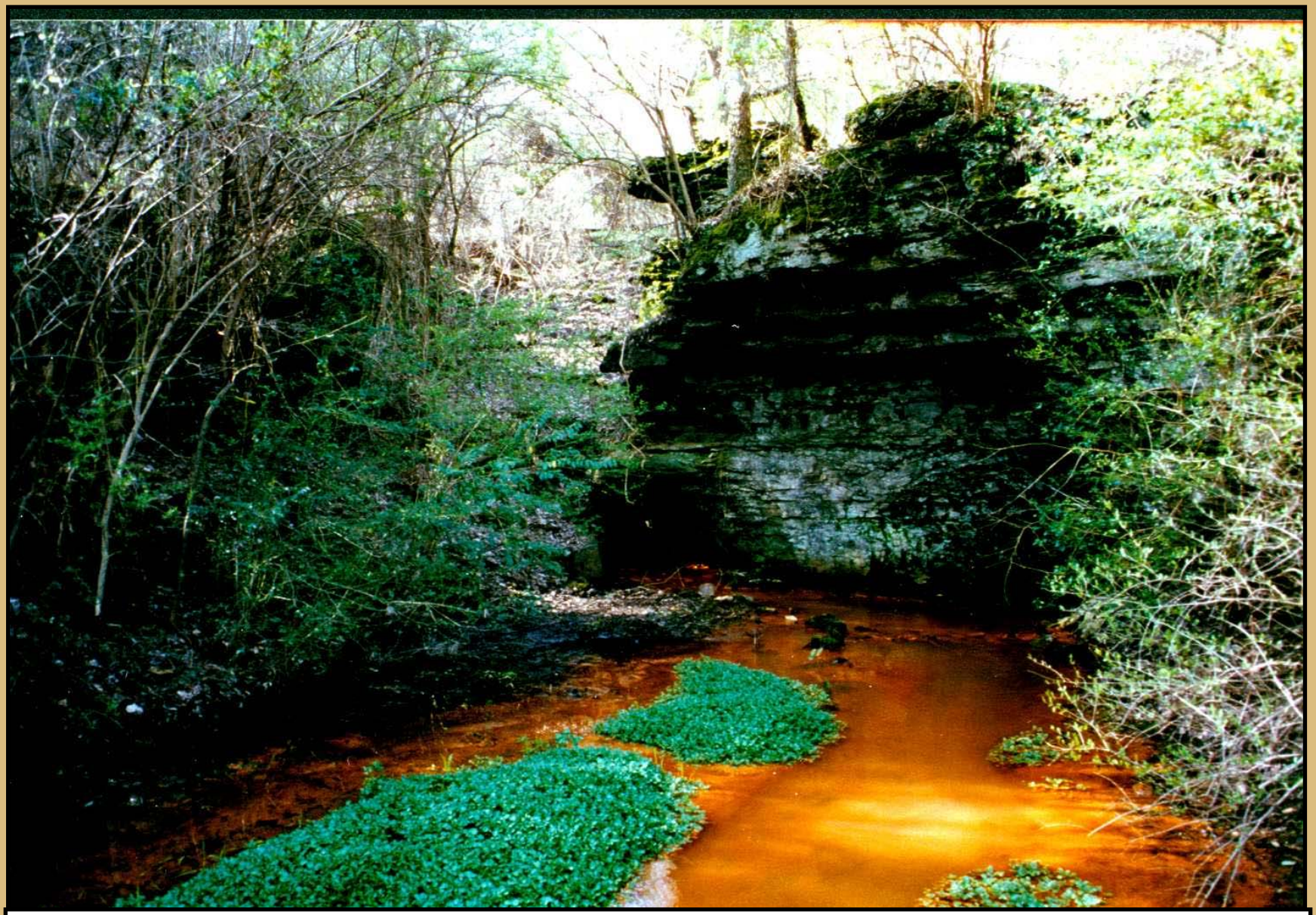
Dye trace of toxic waste discharge well

The USEPA and Kentucky Division of Water assisted by the Center for Cave and Karst Studies discovered 3 factories that were discharging toxic wastes into the karst aquifer and 4 leaking underground gasoline tanks.

Although the owners insisted that this tank was not leaking, upon excavation, 13 holes were discovered along the side of the tank.

Example of Dye Tracer Test to Determine Groundwater Flow in Karst:

"Groundwater Basin Delineation and Site Conceptual Hydrogeologic Model for Saad – Trousdale Superfund, CSX Radnor Yard, and General Electric Service Facility Sites in Nashville, Tennessee"

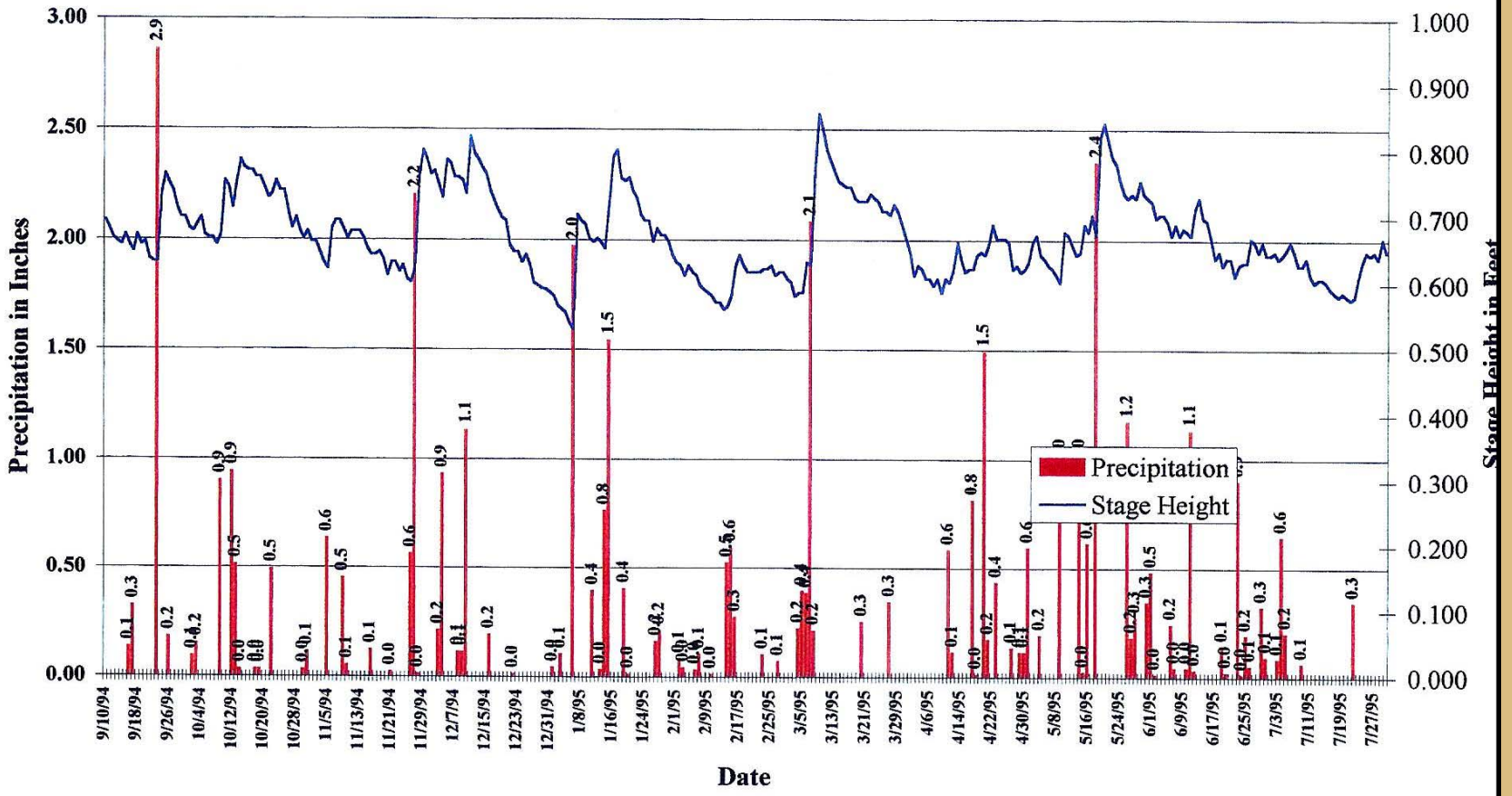


Contaminated Croft Spring at Grassmere Wildlife Park, Nashville, Tennessee

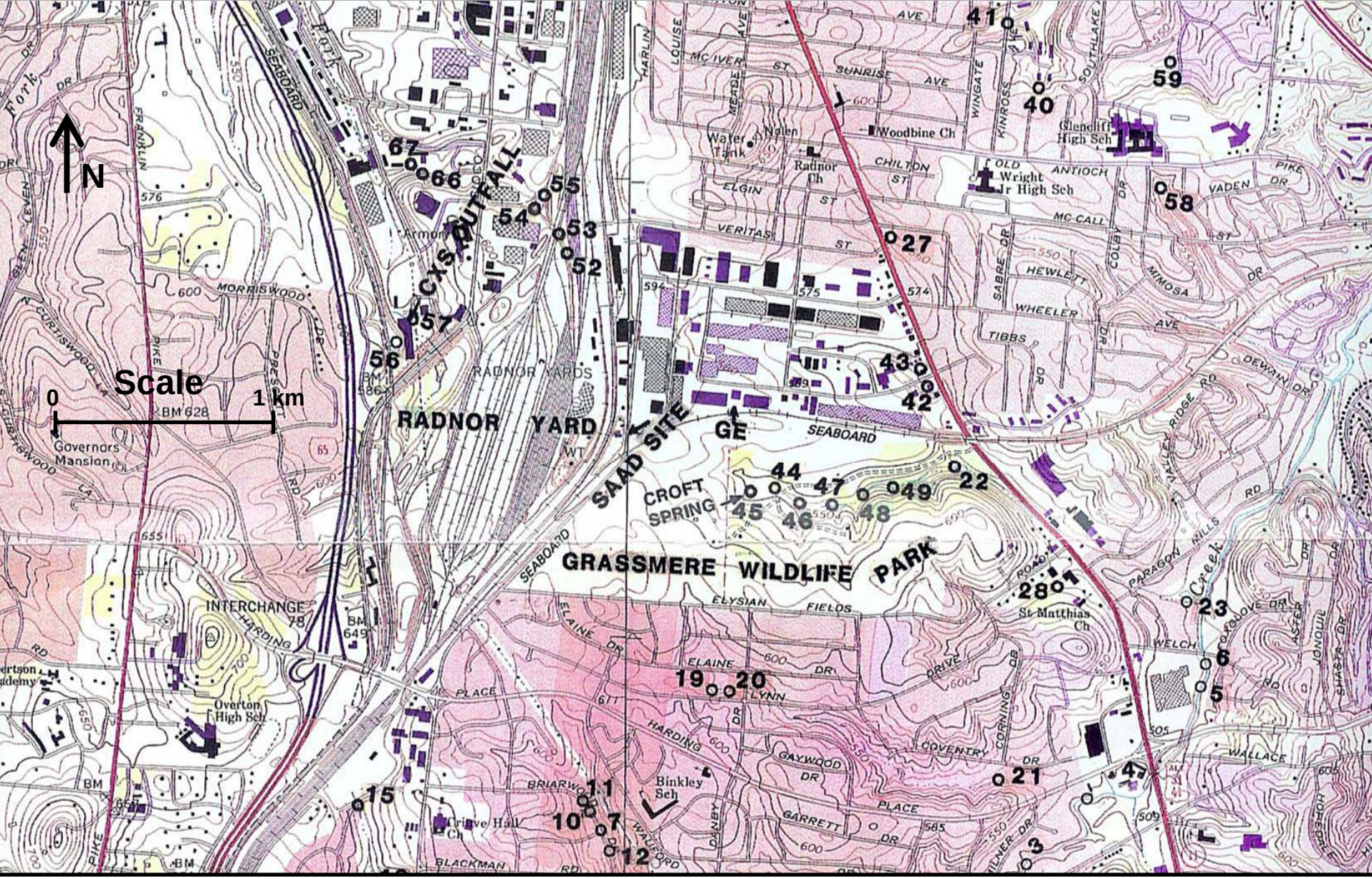
Purpose of Dye Tracer Investigation

- Research performed for U.S. Environmental Protection Agency to determine the source of contamination at Croft Spring
- Three potential sources included:
  - SAAD Oil Superfund Site
  - CSX Railroad Radnor Switching Yard
  - General Electric Factory

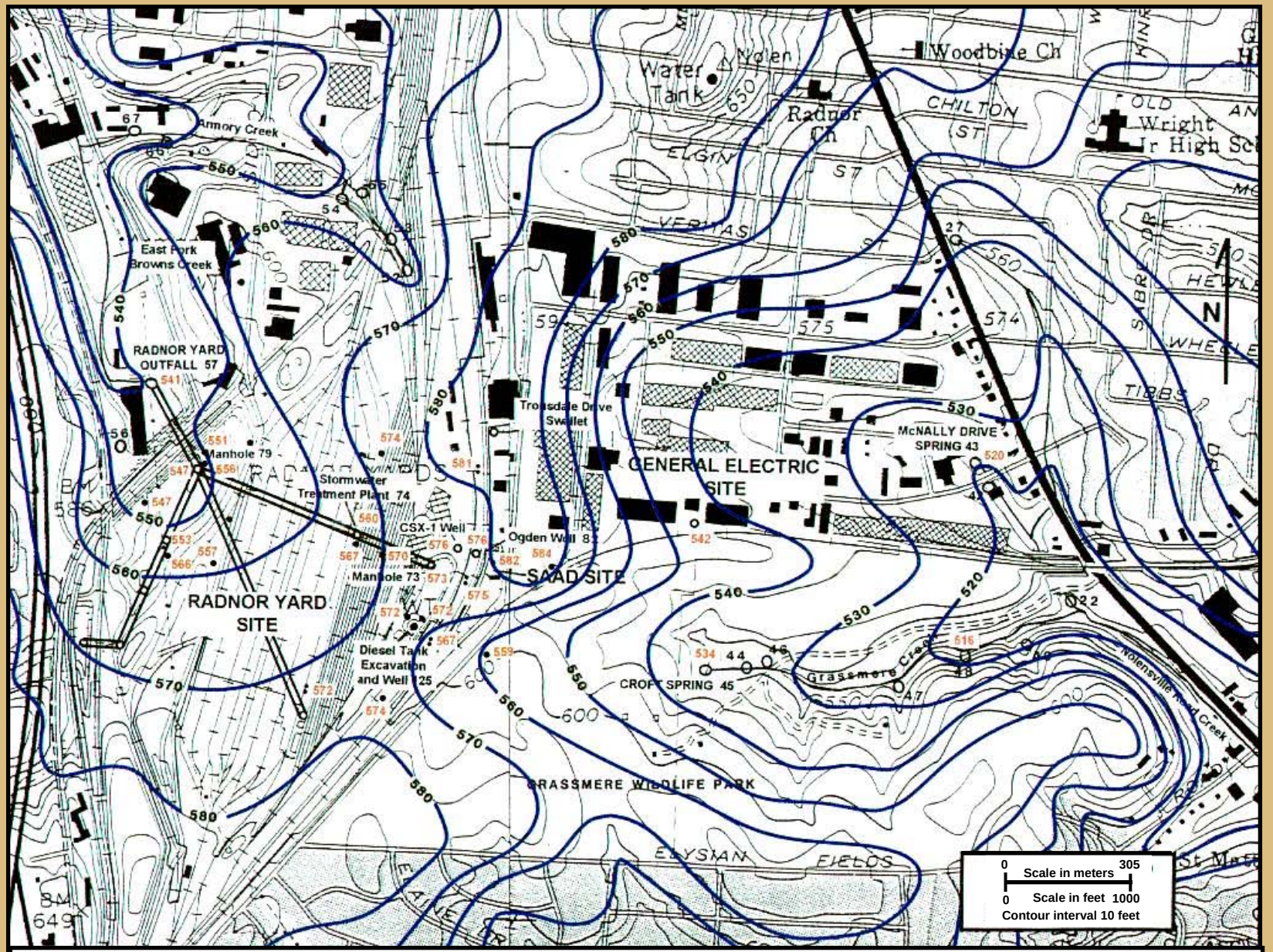
Stage Height vs Precipitation at Croft Spring



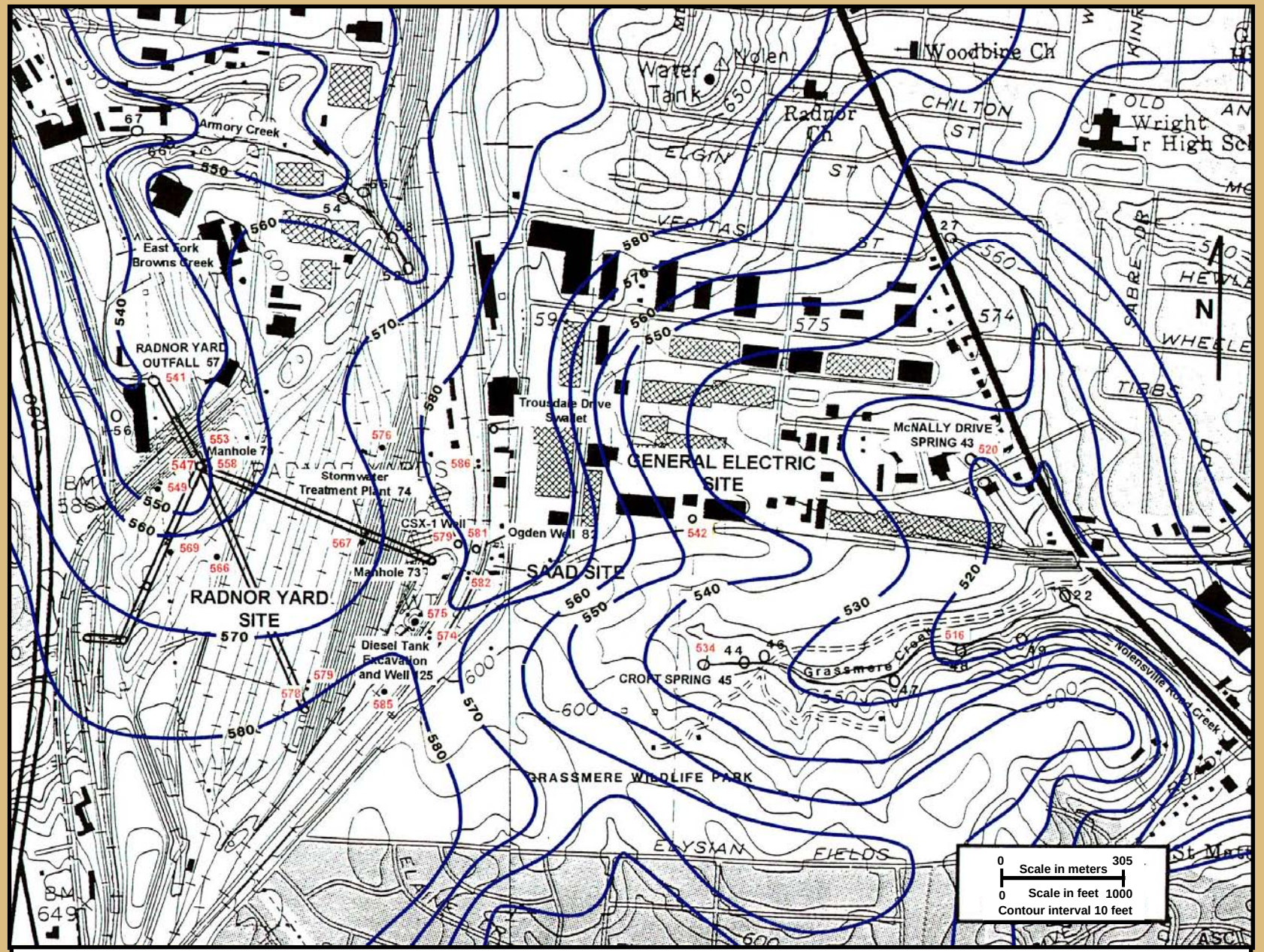
Pressure transducer data logger installed in Croft Spring revealed a stage height fluctuation of only 0.06 m (0.2 ft) over approximately 10 months.



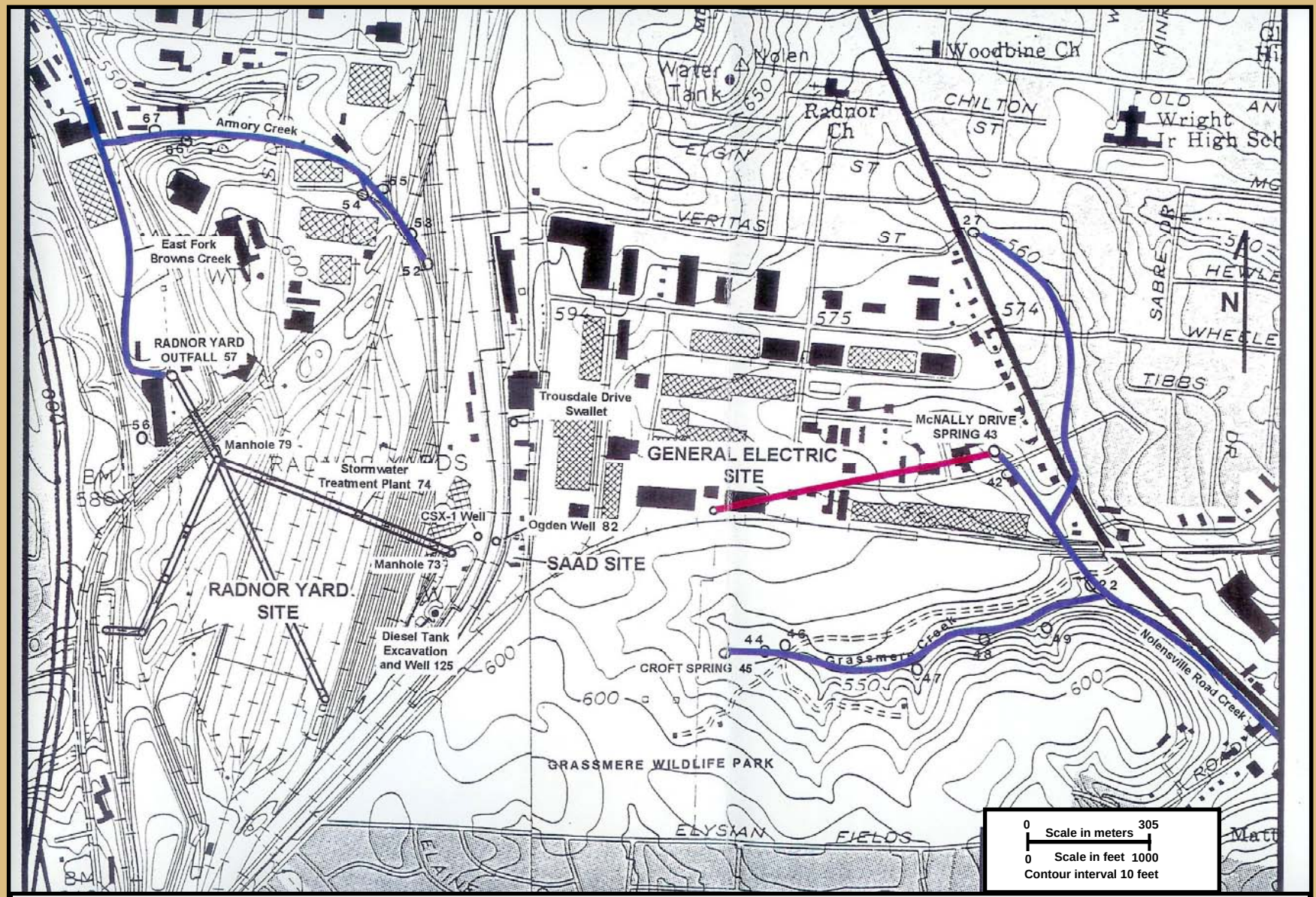
Hydrogeologic inventory and charcoal dye receptor locations in springs, surface streams and monitoring wells. The inventory extended over 100 sq km and included over 70 dye receptor locations.



Water table contours during dry weather conditions, Oct 28, 1994.

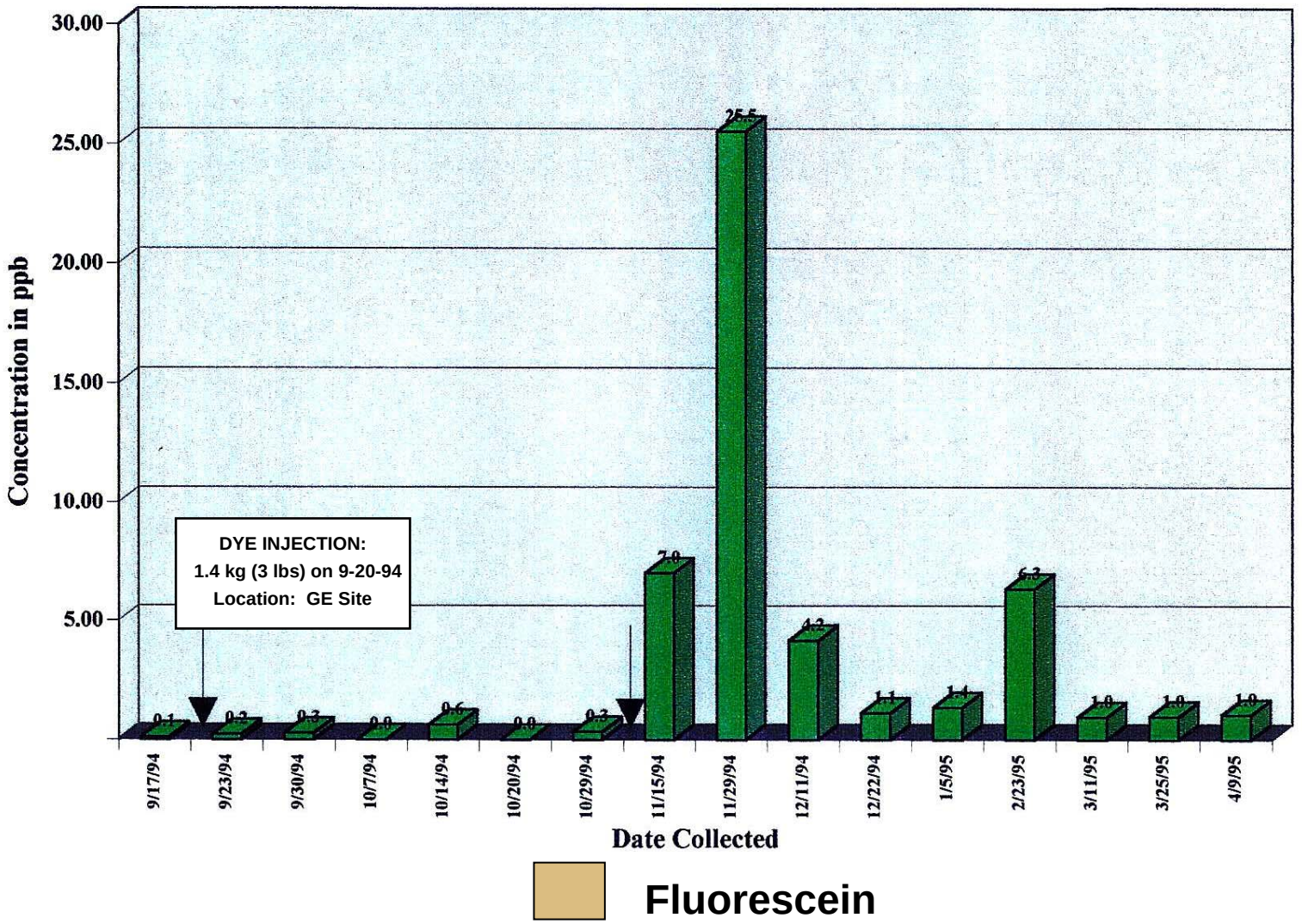


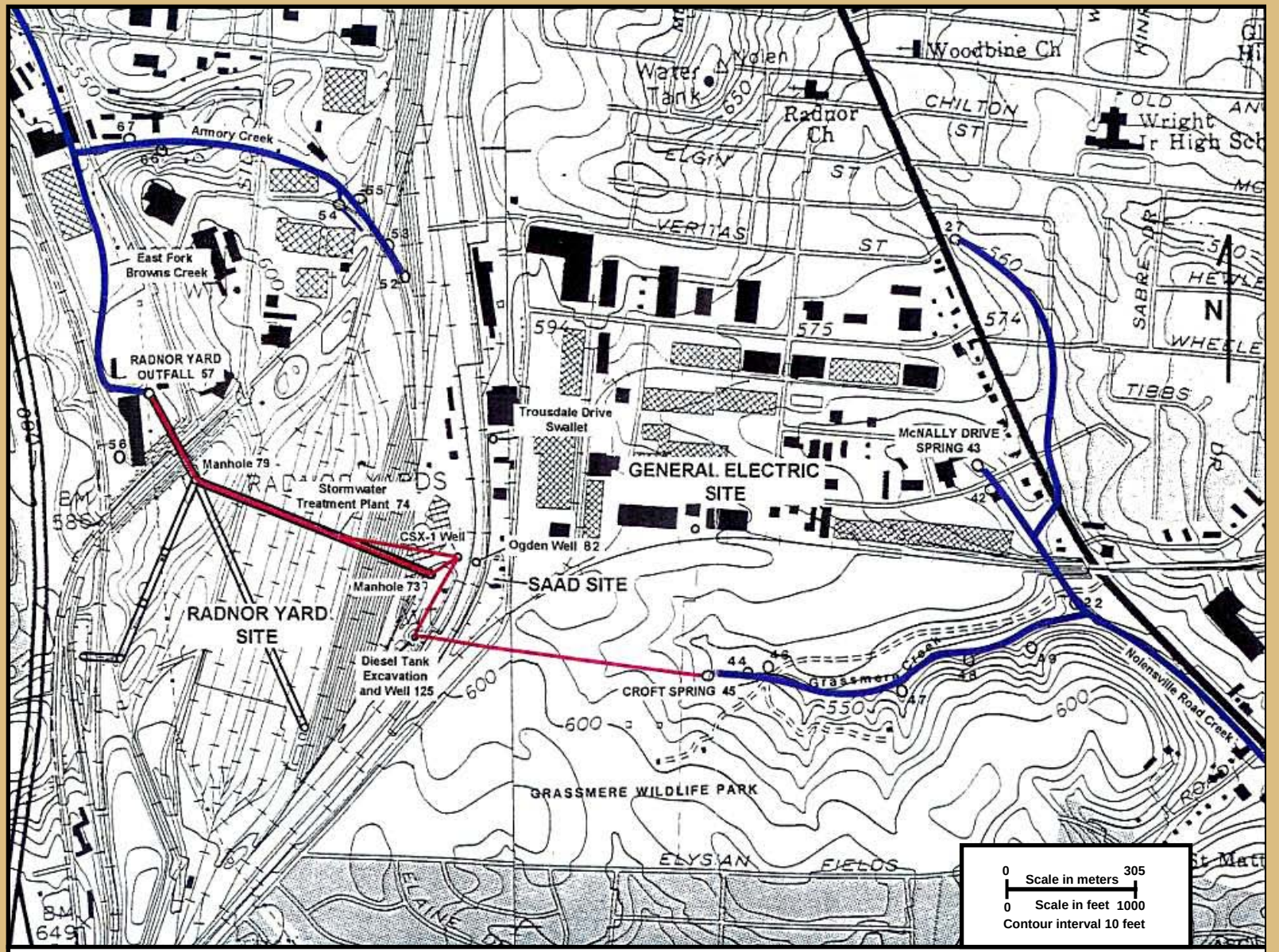
Water table contours during wet weather conditions, March 9, 1995



Fluorescein dye (C.I. Acid Yellow 73) injected into dye injection well at General Electric site was detected 45 days later at McNally Drive Spring.

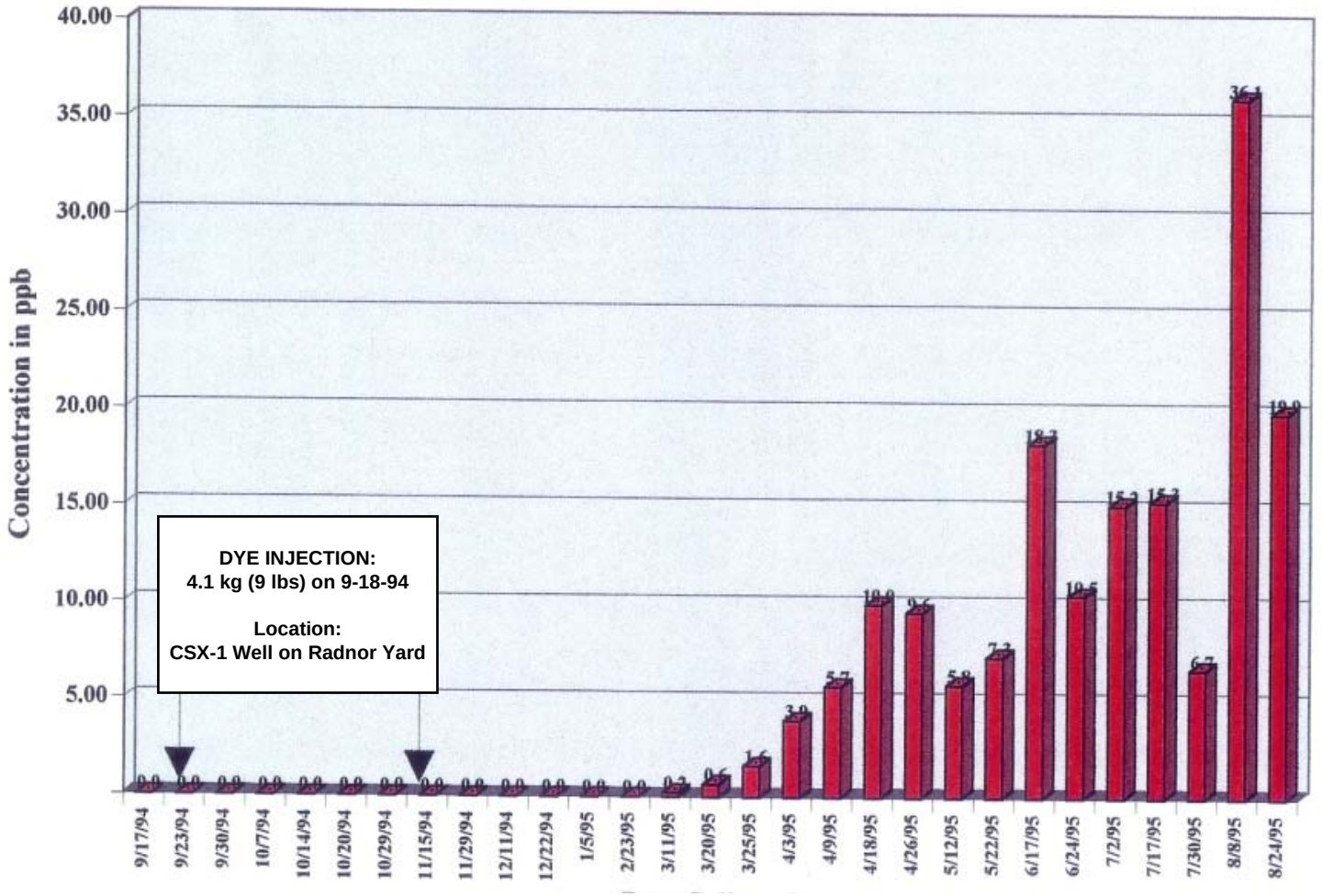
DYE LEVELS AT McNALLY DRIVE SPRING ON NOLENSVILLE ROAD (LOCATION 43) FROM ELUTED CHARCOAL SAMPLES



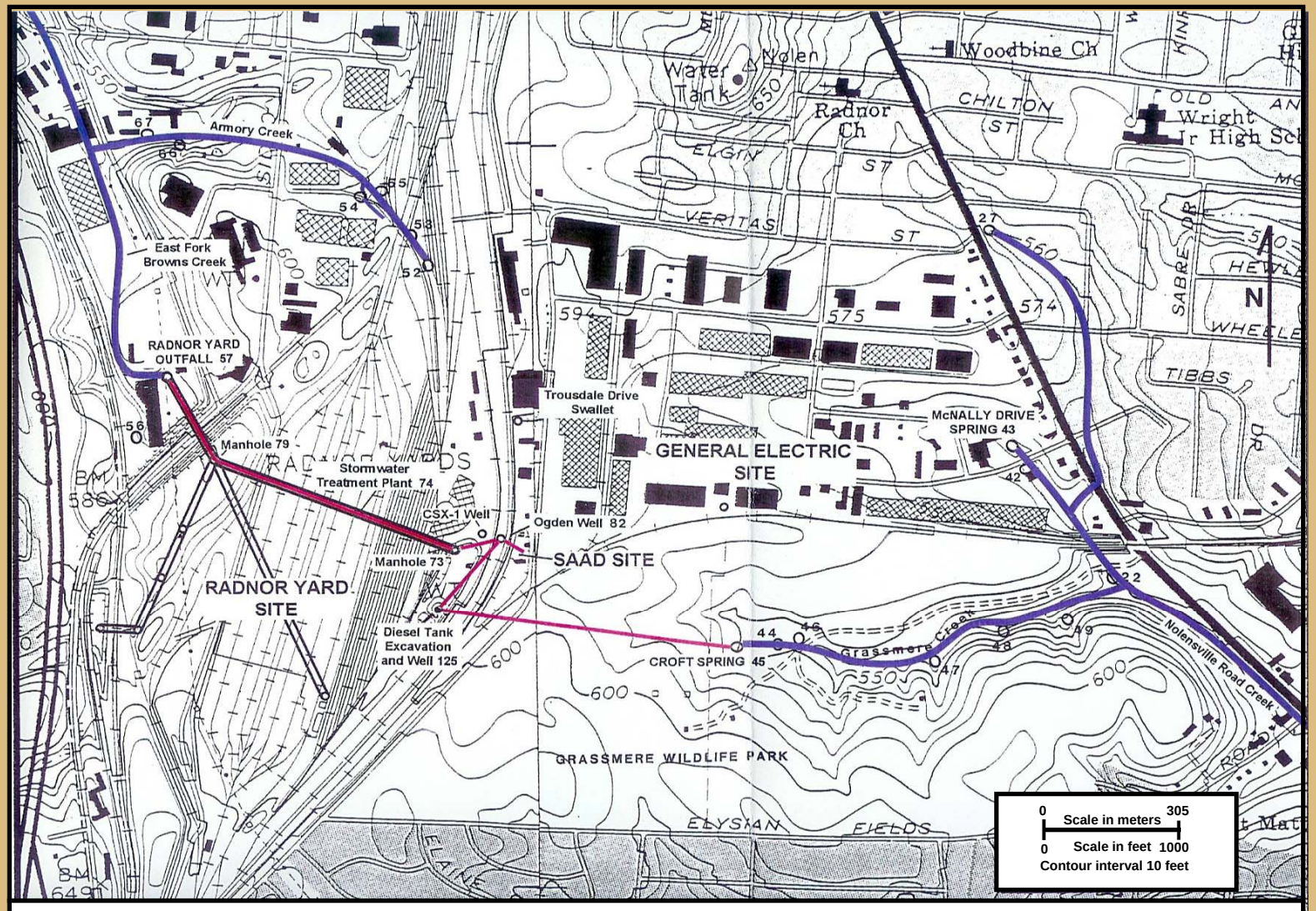


Rhodamine WT (C.I. Acid Red 388) injected into a monitoring well at CSX Railroad Radnor Yard site was detected at Radnor Yard Outfall Spring 102 days later and at Croft Spring 174 days after injection.

DYE LEVELS AT CROFT SPRING (LOCATION 45.1)
FROM ELUTED CHARCOAL SAMPLES



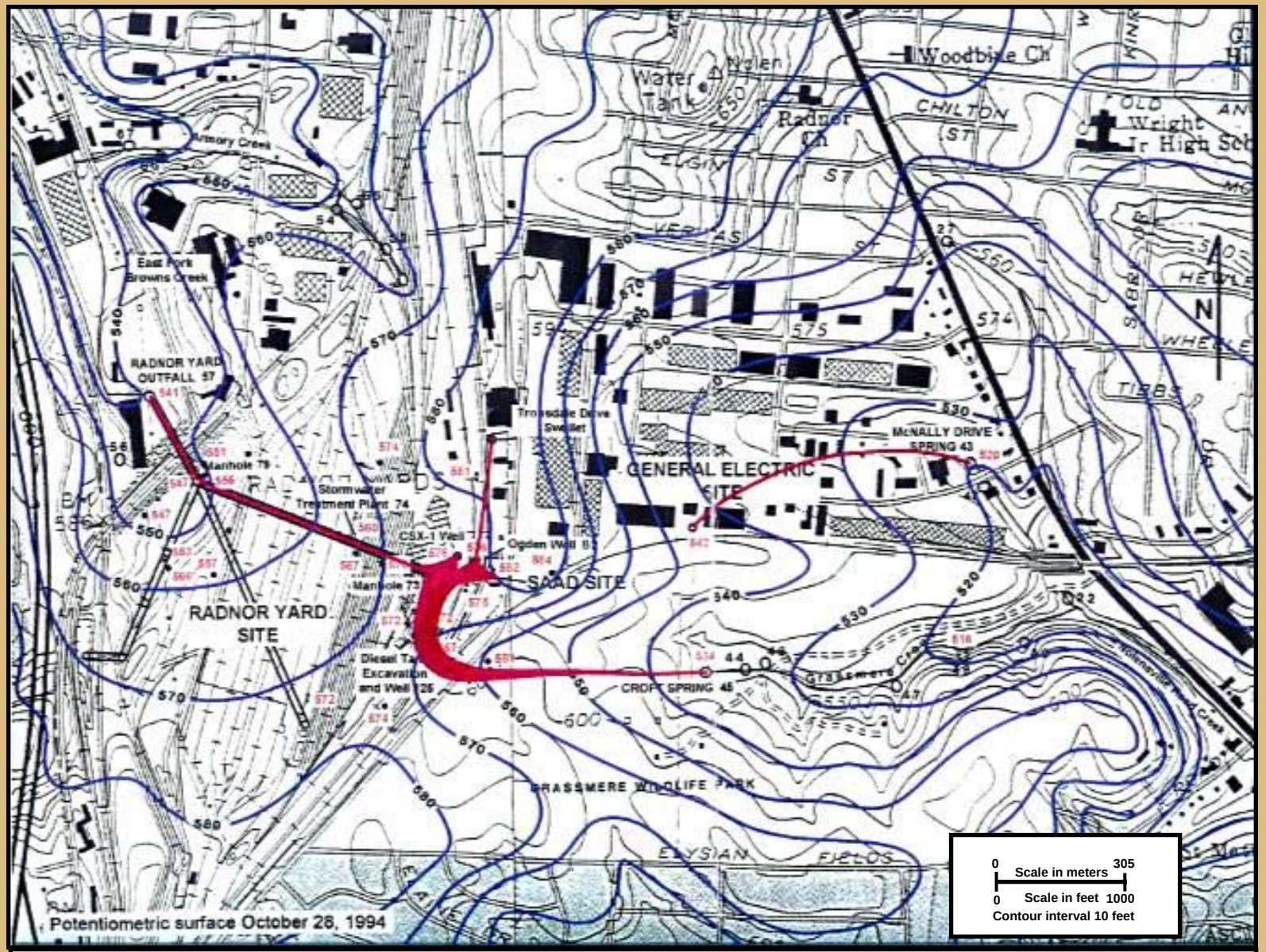
Rhodamine WT



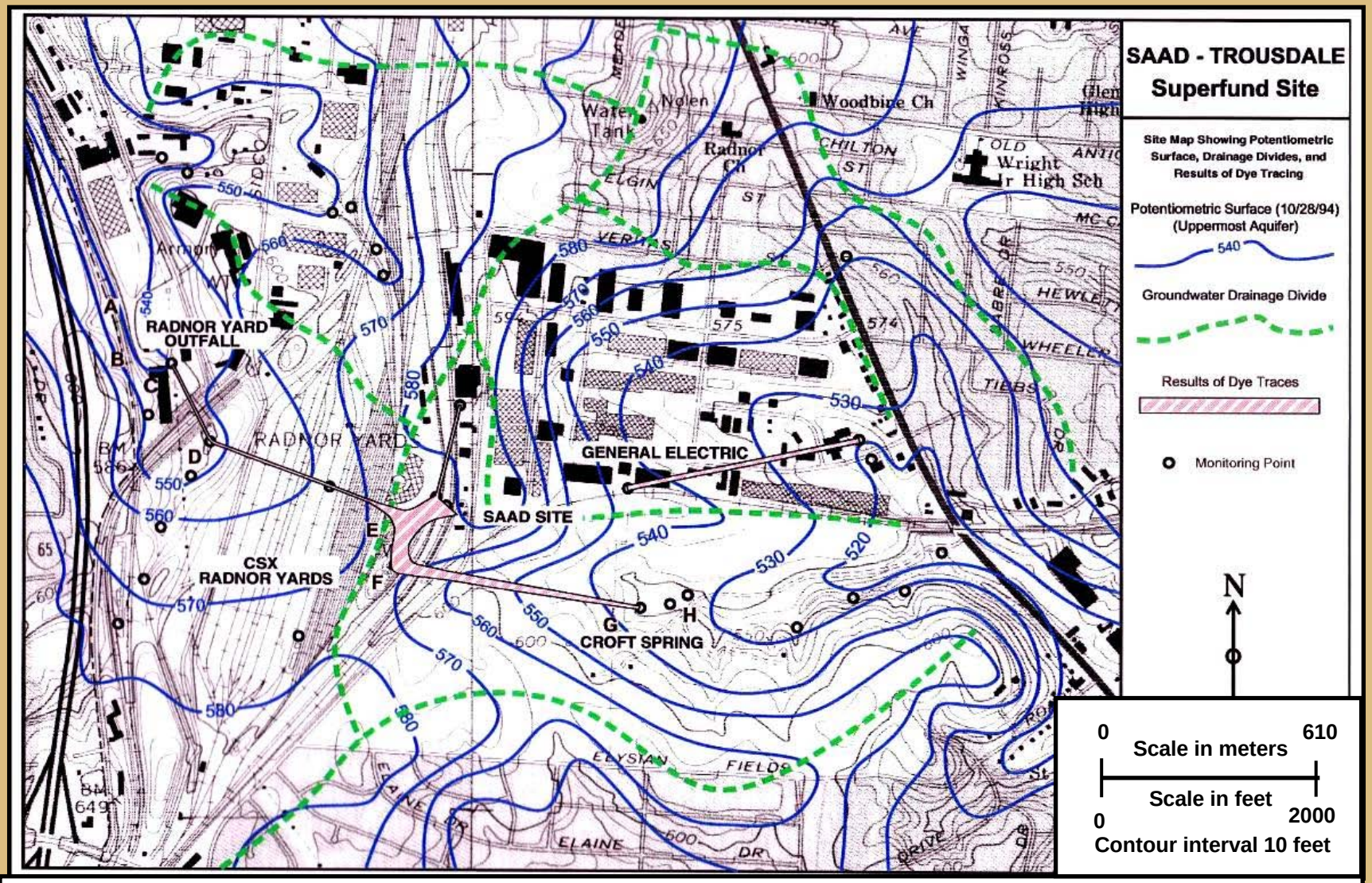
Eosine (C.I. Acid Red 87) injected into a pit at SAAD Oil site was detected 103 days later at both Croft Spring and at CSX Railroad Radnor Yard Outfall Spring.

Groundwater Velocity

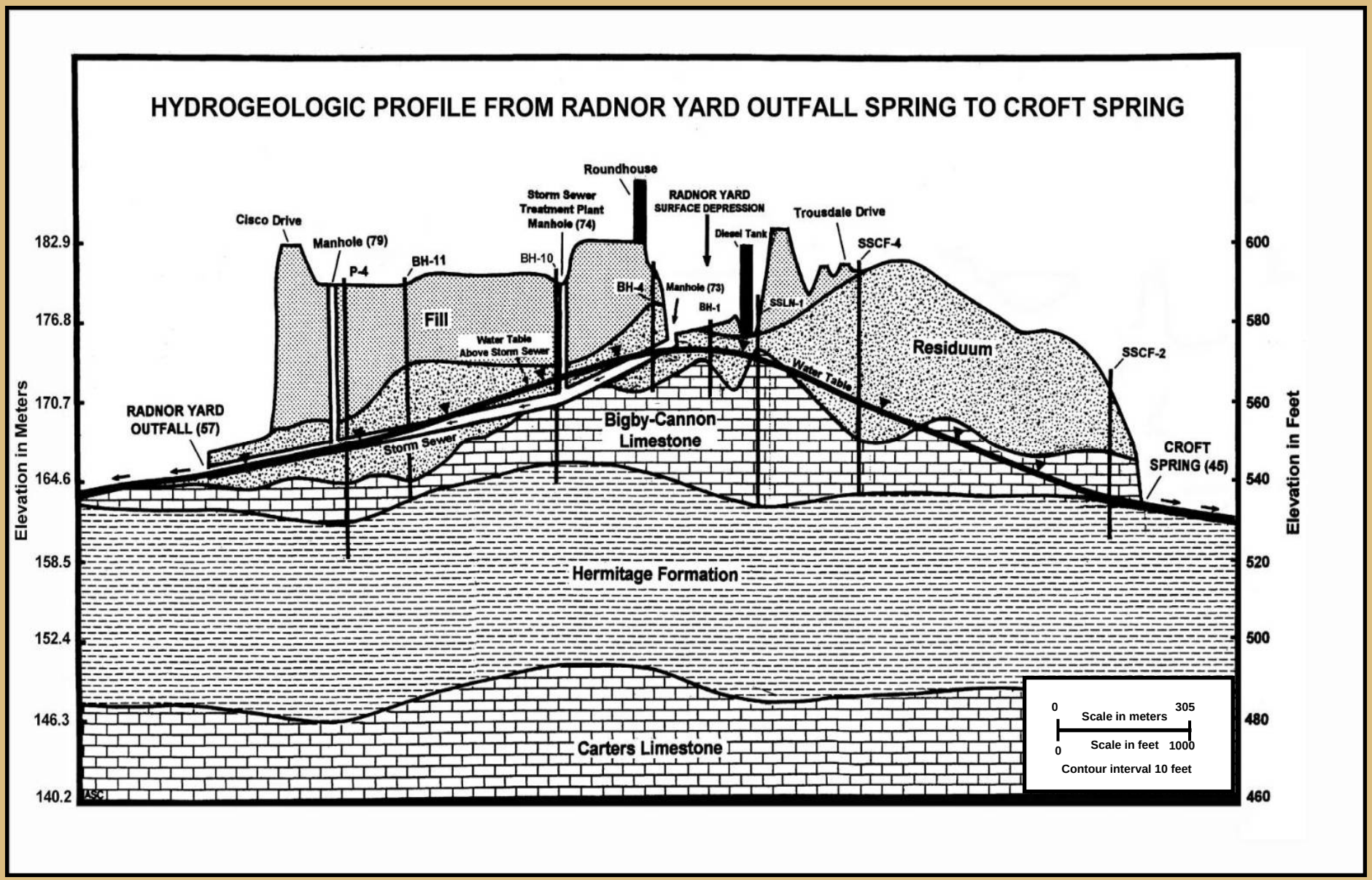
- Dye tracer test indicated flow velocities of 5.25 to 9.43 m/day
- Interestingly, slug tests performed by other consultants indicated a flow rate of 40.2 m/year
- The research provides another example of how slug and pumping tests do not provide valid data in most karst aquifers



Dye tracer test results for 6 dyes injected in the vicinity of the Saad Superfund site.



Site conceptual hydrogeologic model showing water table contours, dye tracer tests and groundwater basin drainage boundaries.


HYDROGEOLOGIC PROFILE FROM RADNOR YARD OUTFALL SPRING TO CROFT SPRING
Roundhouse
Storm Sewer Treatment Plant Manhole (74)
RADNOR YARD SURFACE DEPRESSION
Trousdale Drive
Cisco Drive
Manhole (79)
P-4
BH-11
BH-10
BH-4
Manhole (73)
BH-1
Diesel Tank
SSLN-1
SSCF-4
SSCF-2
Fill
Water Table Above Storm Sewer
Residuum
Water Table
RADNOR YARD OUTFALL (57)
Storm Sewer
Bigby-Cannon Limestone
CROFT SPRING (45)
Hermitage Formation
Carters Limestone
Elevation in Meters
182.9
176.8
170.7
164.6
158.5
152.4
146.3
140.2
Elevation in Feet
600
580
560
540
520
500
480
460
0
Scale in meters
305
0
Scale in feet
1000
Contour interval 10 feet

Results of Dye Tracer Investigation

1. Groundwater from General Electric site flows only to McNally Drive Spring. Therefore General Electric is not responsible for Croft Spring contamination.

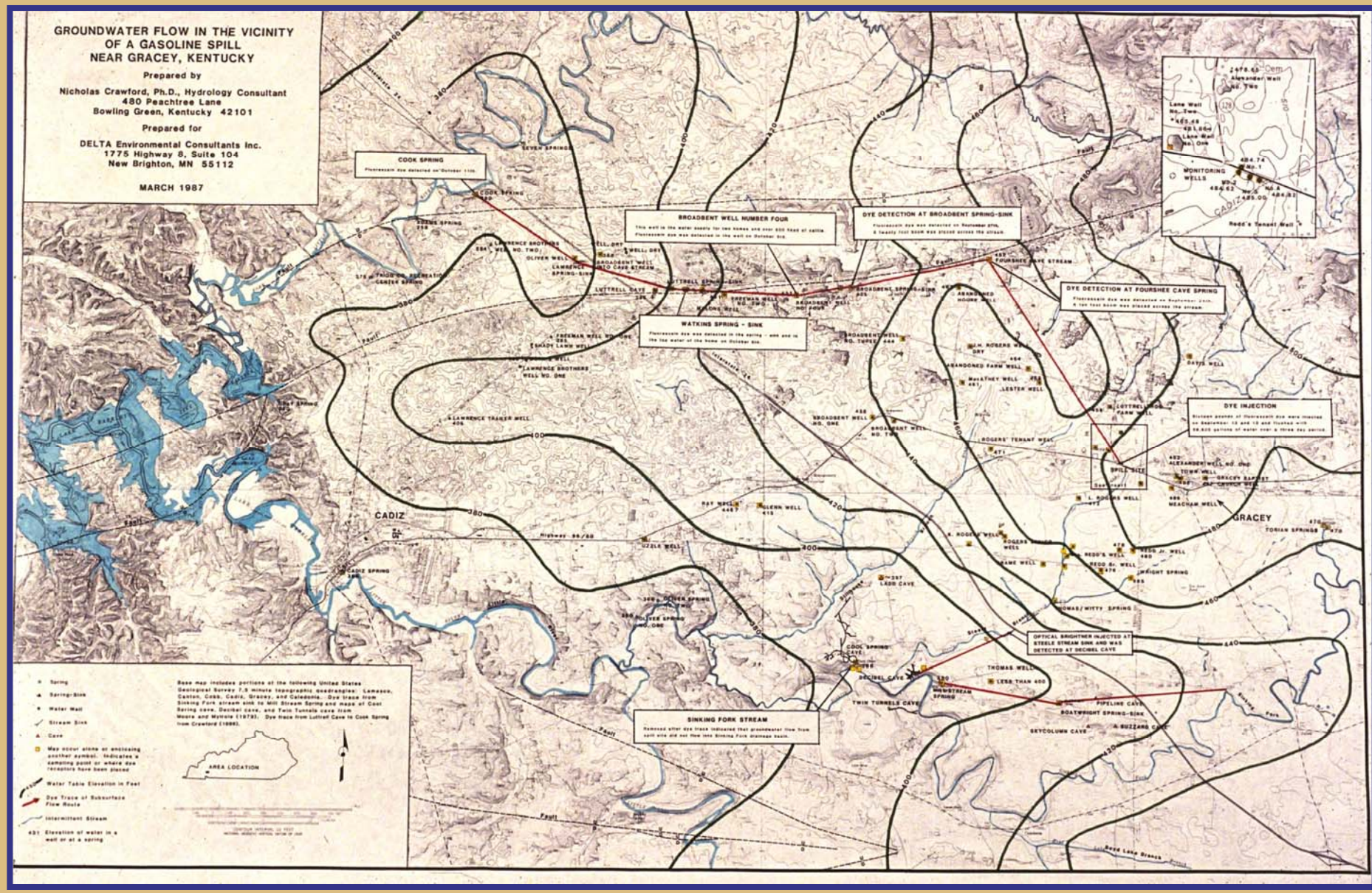
2. Groundwater from both the SAAD Superfund site and the CSX Radnor Yard flowed to both Croft Spring and to the Radnor Yard Outfall Spring. SAAD and CSX therefore share the responsibility for contamination.

3. The site conceptual hydrogeologic model identified the groundwater flow directions, the approximate boundaries for the several groundwater basins and explained the interrelationship between groundwater flow and geology.

Research Procedures

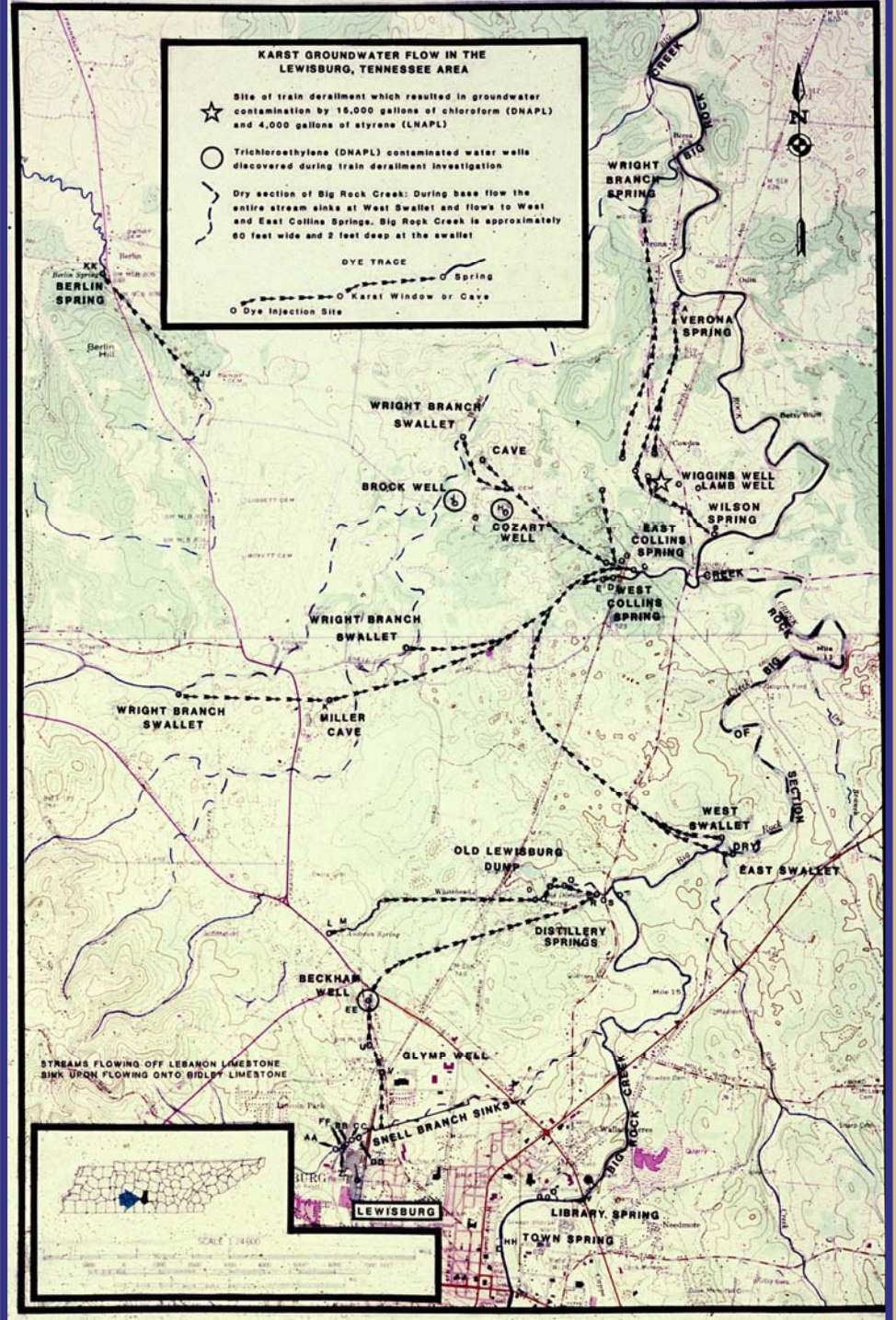
- Karst hydrogeologic inventory
- Croft Spring stage hydrograph analysis
- Charcoal dye receptor placement and background analysis
- Matrix interference analysis
- Water table investigation
- Geologic investigation
- Dye injection of 6 fluorescent dyes
- Activated charcoal dye receptor elutant analysis performed by synchronous scanning on a Shimadzu RF-5301PC Spectrofluorophotometer
- Preparation of site conceptual hydrogeologic model

Emergency Response to Spills of Hazardous Liquids on Karst Terrains

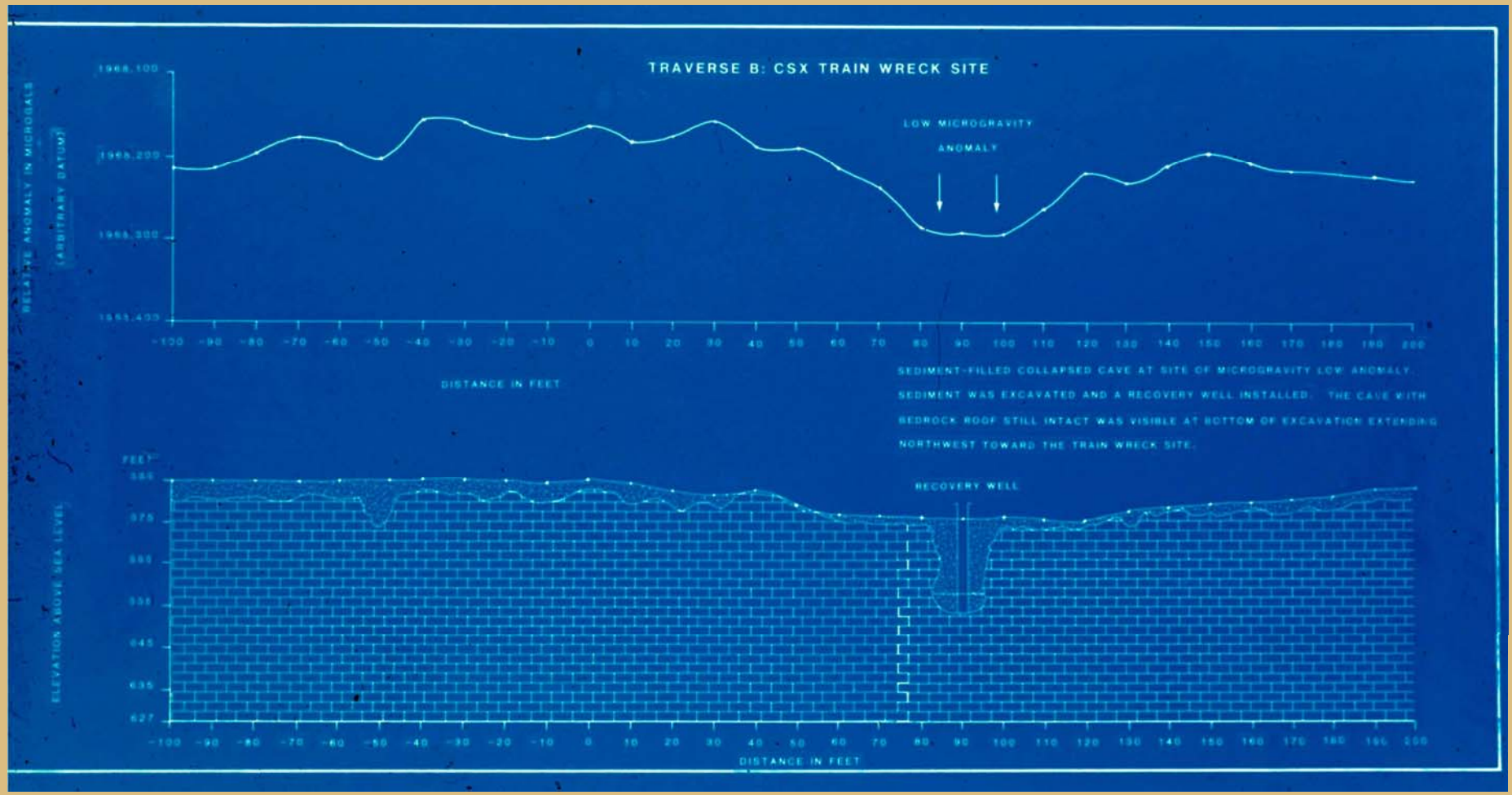

GROUNDWATER FLOW IN THE VICINITY OF A GASOLINE SPILL NEAR GRACEY, KENTUCKY
Prepared by
Nicholas Crawford, Ph.D., Hydrology Consultant
480 Peachtree Lane
Bowling Green, Kentucky 42101
Prepared for
DELTA Environmental Consultants Inc.
1775 Highway 8, Suite 104
New Brighton, MN 55112
MARCH 1987
COOK SPRING
BROADBENT WELL NUMBER FOUR
DYE DETECTION AT BROADBENT SPRING-SINK
DYE DETECTION AT FOURSHEE CAVE SPRING
WATKINS SPRING - SINK
DYE INJECTION
OPTICAL BRIGHTNER INJECTED AT STEELE STREAM SINK AND WAS DETECTED AT DECIBEL CAVE
SINKING FORK STREAM
CADIZ
GRACEY
Highway 68/80
Fault
Spring
Spring-Sink
Water Well
Stream Sink
Cave
Water Table Elevation in Feet
Dye Trace of Subsurface Flow Route
Intermittent Stream
AREA LOCATION


UNI-TEMP


VTOI

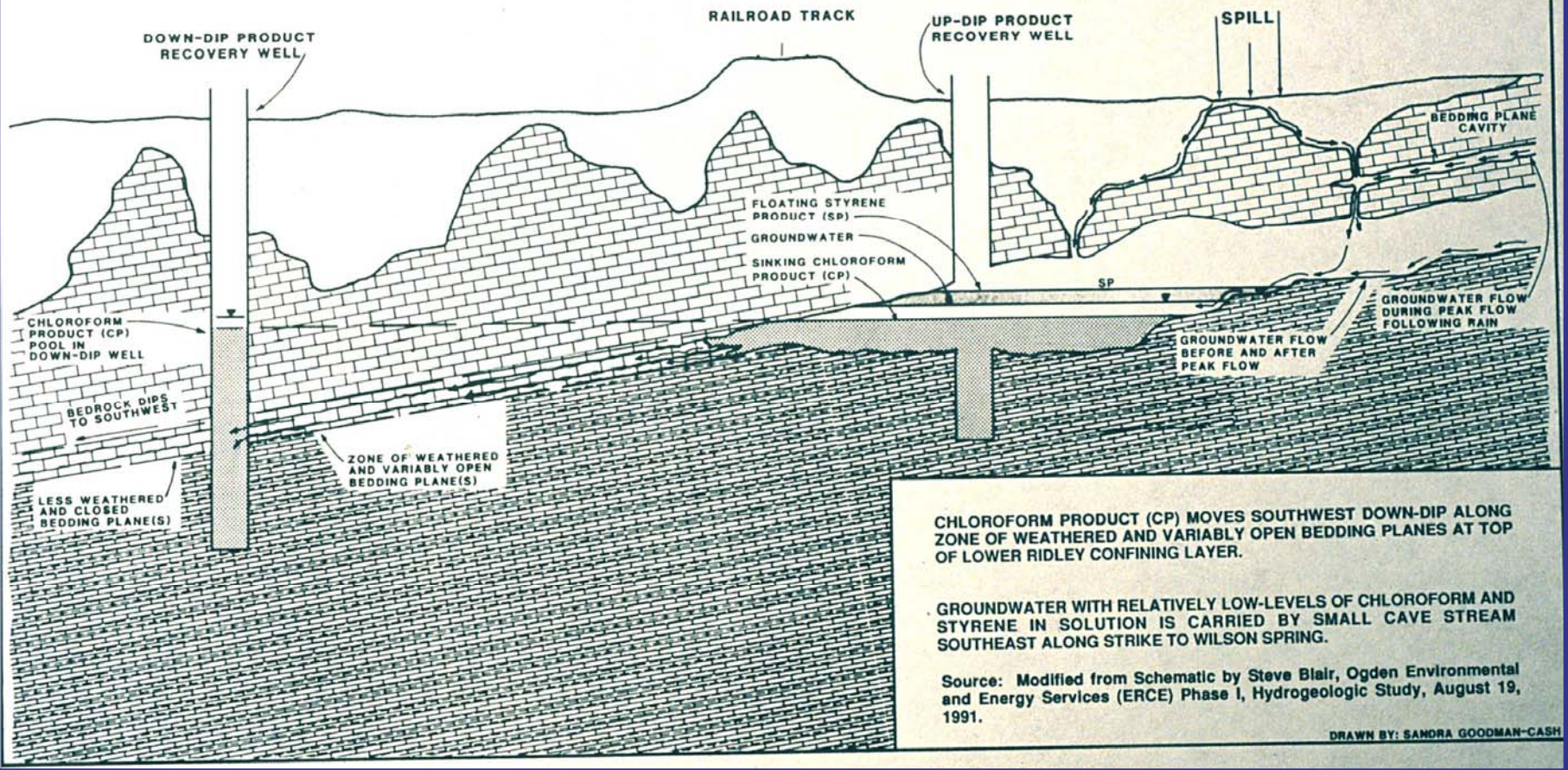

KARST GROUNDWATER FLOW IN THE LEWISBURG, TENNESSEE AREA
Site of train derailment which resulted in groundwater contamination by 15,000 gallons of chloroform (DNAPL) and 4,000 gallons of styrene (LNAPL)
Trichloroethylene (DNAPL) contaminated water wells discovered during train derailment investigation
Dry section of Big Rock Creek: During base flow the entire stream sinks at West Swallet and flows to West and East Collins Springs. Big Rock Creek is approximately 60 feet wide and 2 feet deep at the swallet
DYE TRACE
Spring
Karst Window or Cave
Dye Injection Site
BERLIN SPRING
WRIGHT BRANCH SPRING
VERONA SPRING
WRIGHT BRANCH SWALLET
CAVE
BROCK WELL
COZART WELL
WIGGINS WELL
LAMB WELL
WILSON SPRING
EAST COLLINS SPRING
WEST COLLINS SPRING
WRIGHT BRANCH SWALLET
WRIGHT BRANCH SWALLET
MILLER CAVE
BIG ROCK CREEK
DRY SECTION OF
WEST SWALLET
EAST SWALLET
OLD LEWISBURG DUMP
DISTILLERY SPRINGS
BECKHAM WELL
GLYMP WELL
STREAMS FLOWING OFF LEBANON LIMESTONE SINK UPON FLOWING ONTO BIDLEY LIMESTONE
SNELL BRANCH SINKS
LEWISBURG
LIBRARY SPRING
TOWN SPRING


diet
Coke
473 mL


TRAVERSE B: CSX TRAIN WRECK SITE
RELATIVE ANOMALY IN MICROGALS (ARBITRARY DATUM)
1968.100
1968.200
1968.300
1968.400
LOW MICROGRAVITY ANOMALY
-100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
DISTANCE IN FEET
SEDIMENT-FILLED COLLAPSED CAVE AT SITE OF MICROGRAVITY LOW ANOMALY. SEDIMENT WAS EXCAVATED AND A RECOVERY WELL INSTALLED. THE CAVE WITH BEDROCK ROOF STILL INTACT WAS VISIBLE AT BOTTOM OF EXCAVATION EXTENDING NORTHWEST TOWARD THE TRAIN WRECK SITE.
FEET
ELEVATION ABOVE SEA LEVEL
975
955
935
915
895
627
RECOVERY WELL
-100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
DISTANCE IN FEET

SCHEMATIC OF HYDROGEOLOGY AND CONTAMINANT MOVEMENT AT TRAIN DERAILMENT SITE

NOT TO SCALE

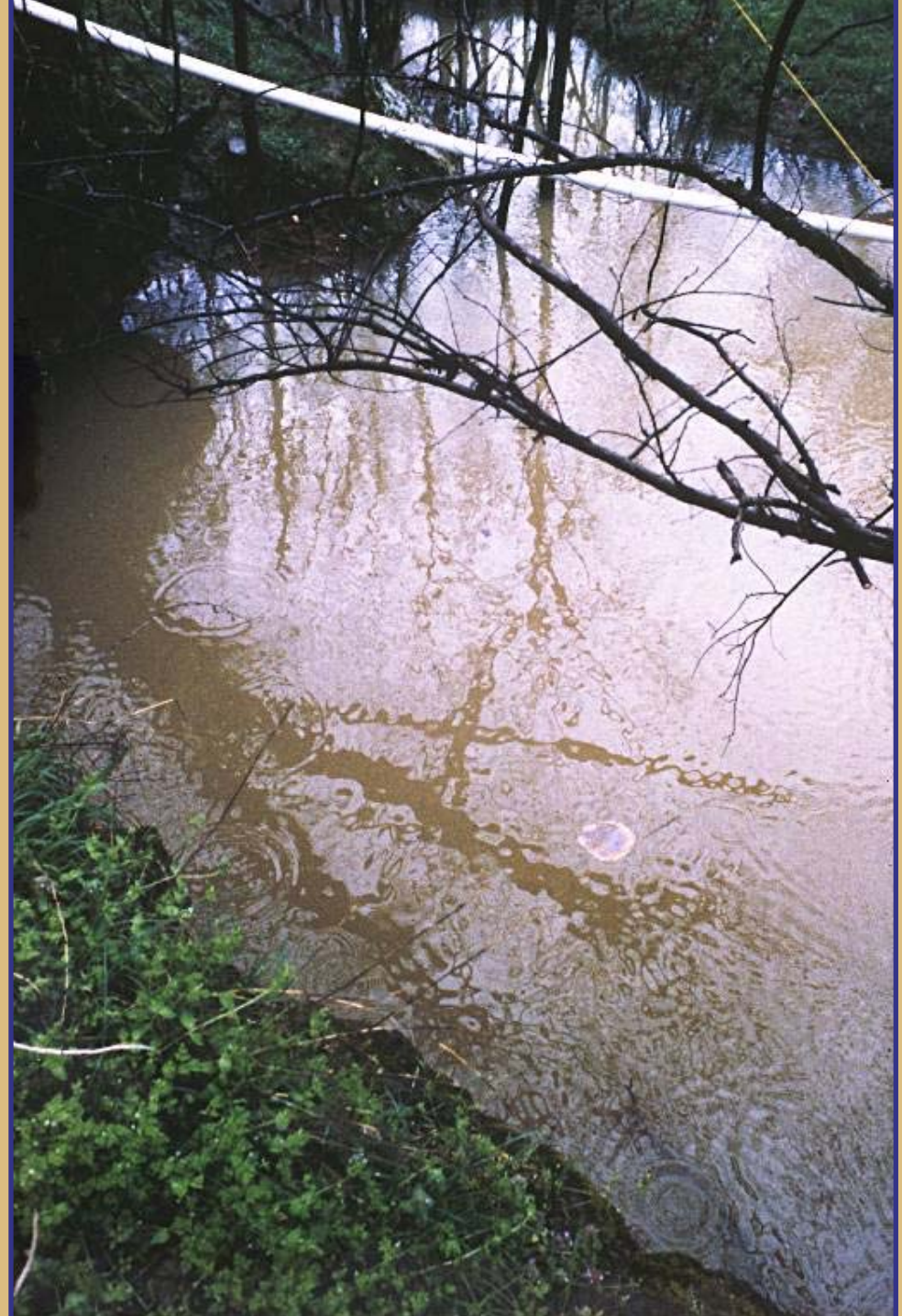


CHLOROFORM PRODUCT (CP) MOVES SOUTHWEST DOWN-DIP ALONG ZONE OF WEATHERED AND VARIABLY OPEN BEDDING PLANES AT TOP OF LOWER RIDLEY CONFINING LAYER.

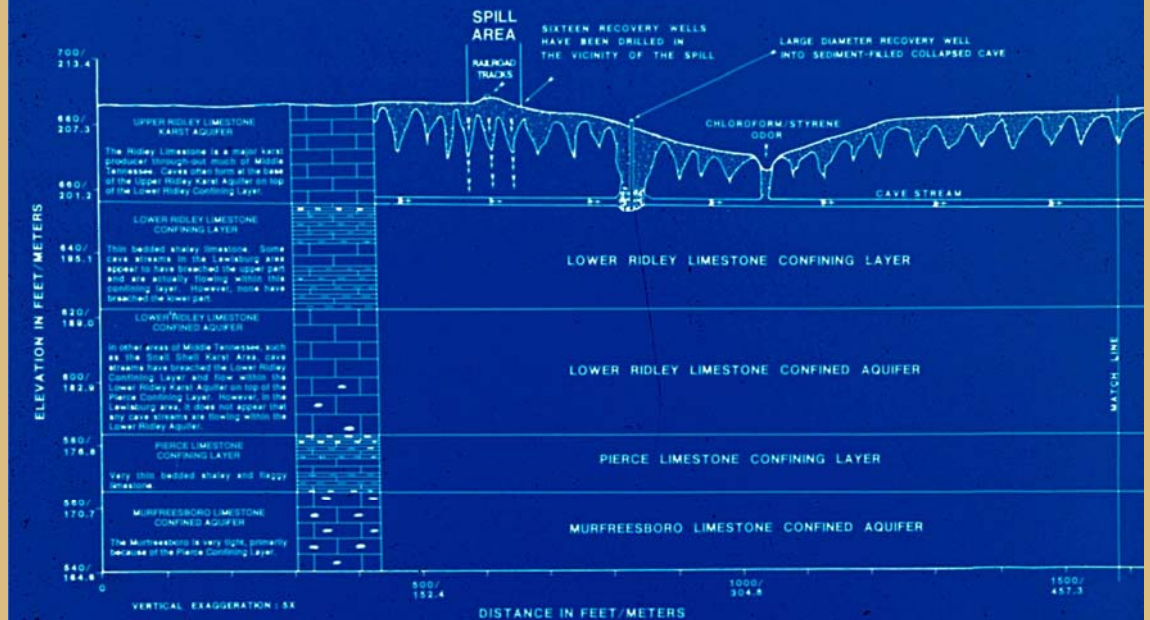
GROUNDWATER WITH RELATIVELY LOW-LEVELS OF CHLOROFORM AND STYRENE IN SOLUTION IS CARRIED BY SMALL CAVE STREAM SOUTHEAST ALONG STRIKE TO WILSON SPRING.

Source: Modified from Schematic by Steve Blair, Ogden Environmental and Energy Services (ERCE) Phase I, Hydrogeologic Study, August 19, 1991.

DRAWN BY: SANDRA GOODMAN-CASH

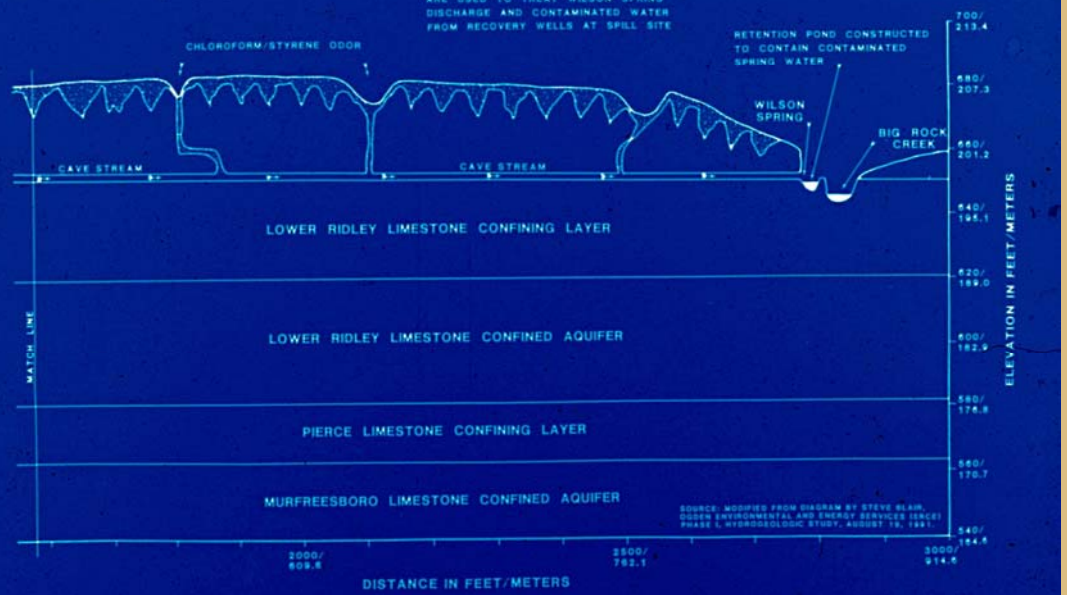


HYDROGEOLOGY IN THE VICINITY OF TRAIN DERAILMENT



TREATMENT SYSTEM AT WILSON SPRING

AIR STRIPPERS AND ACTIVATED CARBON ARE USED TO TREAT WILSON SPRING DISCHARGE AND CONTAMINATED WATER FROM RECOVERY WELLS AT SPILL SITE

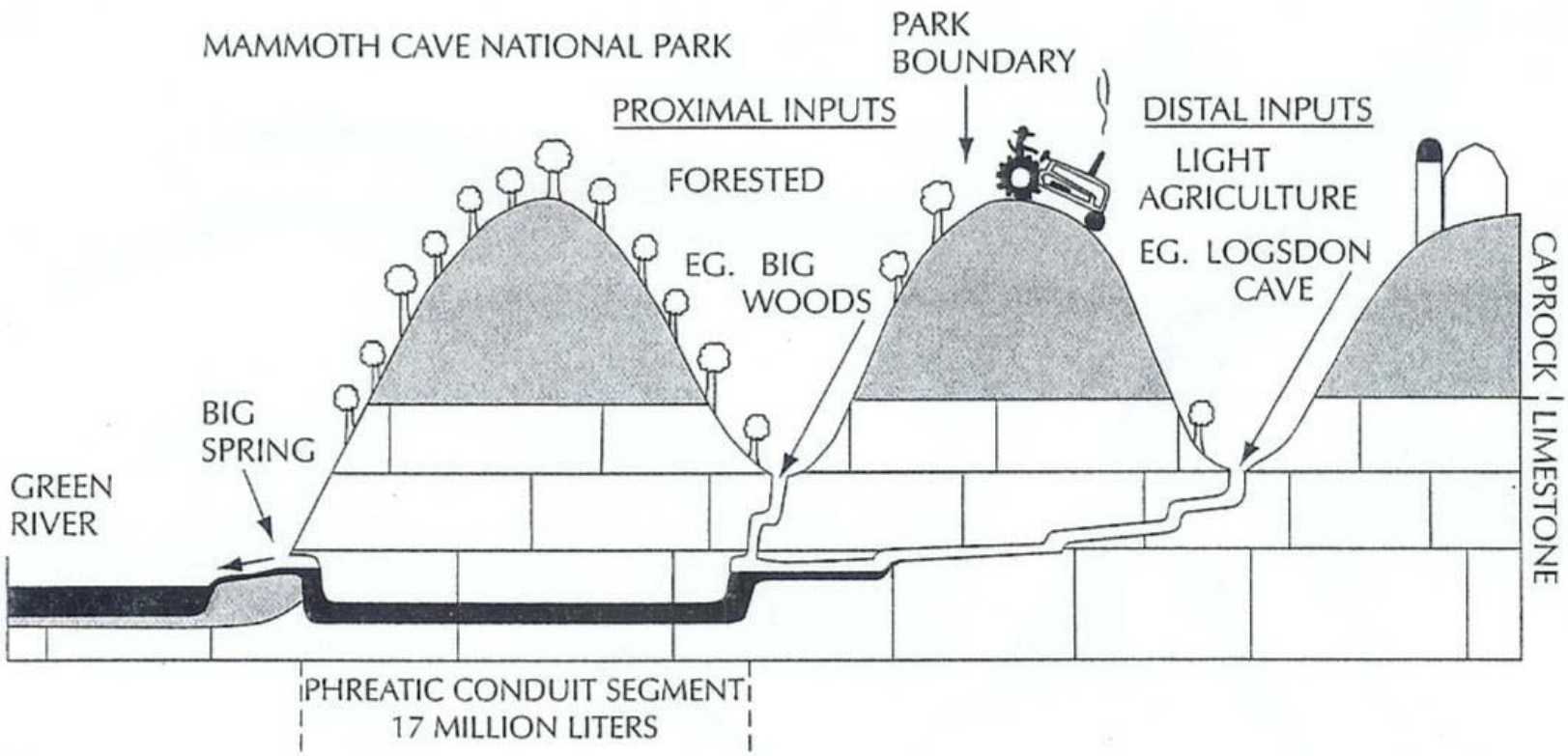


SOURCE: MODIFIED FROM DIAGRAM BY STEVE BLAIR, OGDEN ENVIRONMENTAL AND ENERGY SERVICES (OE&E) PHASE I, HYDROGEOLOGIC STUDY, AUGUST 19, 1991.

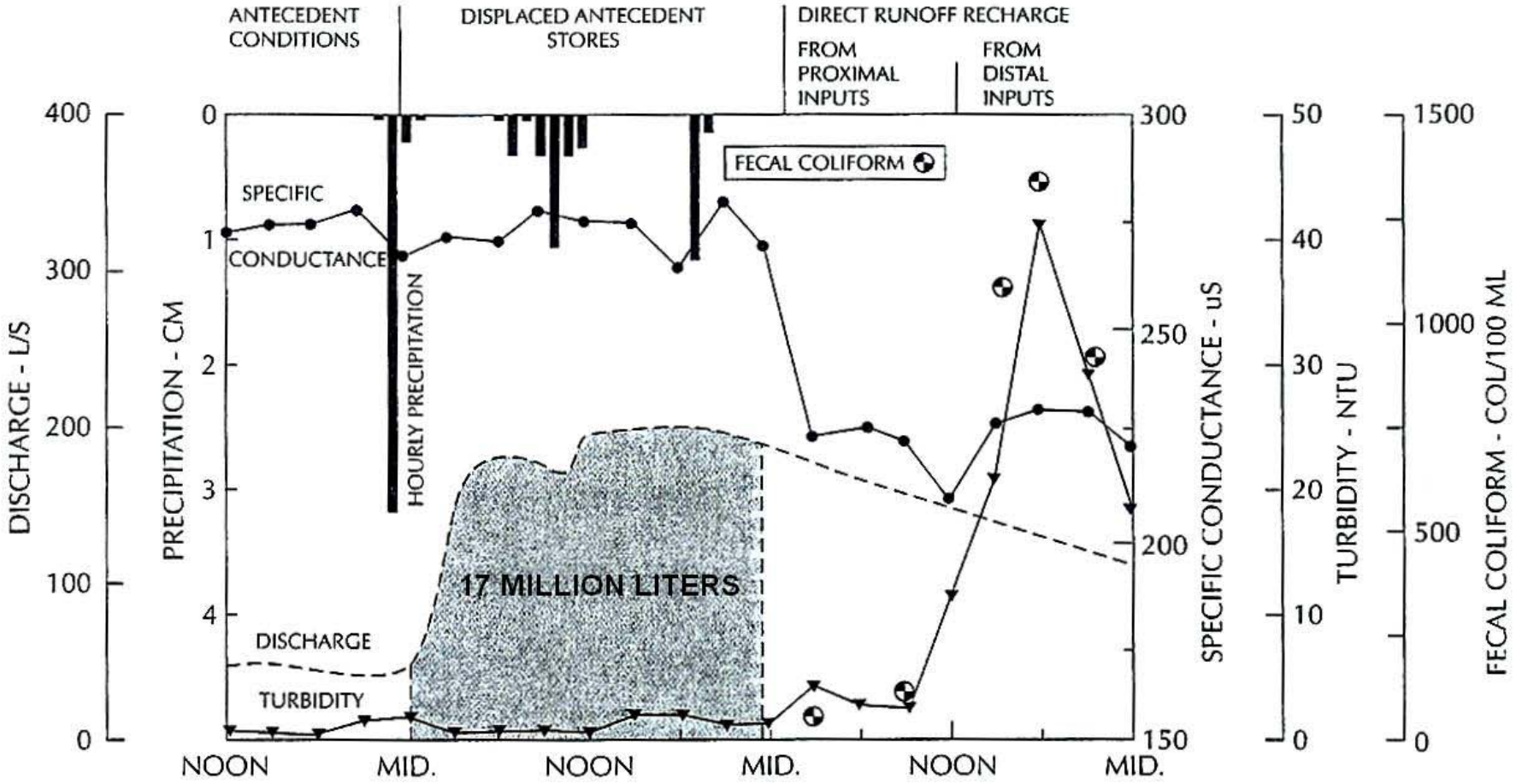
DRAWN BY: SANDRA GOODMAN

The Flux of Contaminants Through Free-Flow Karst Aquifers and Monitoring Techniques

THE FLUX OF NON-POINT SOURCE CONTAMINANTS THROUGH FREE-FLOW KARST AQUIFERS



Diagrammatic cross section of the Big Spring ground-water basin of Mammoth Cave National Park. Note the phreatic conduit section that is below the water table. *Source: M. Ryan and J. Meiman* Ground Water, *34, no. 1 (1996):23 to 30. © Ground Water Publishing Company. Used with permission.*

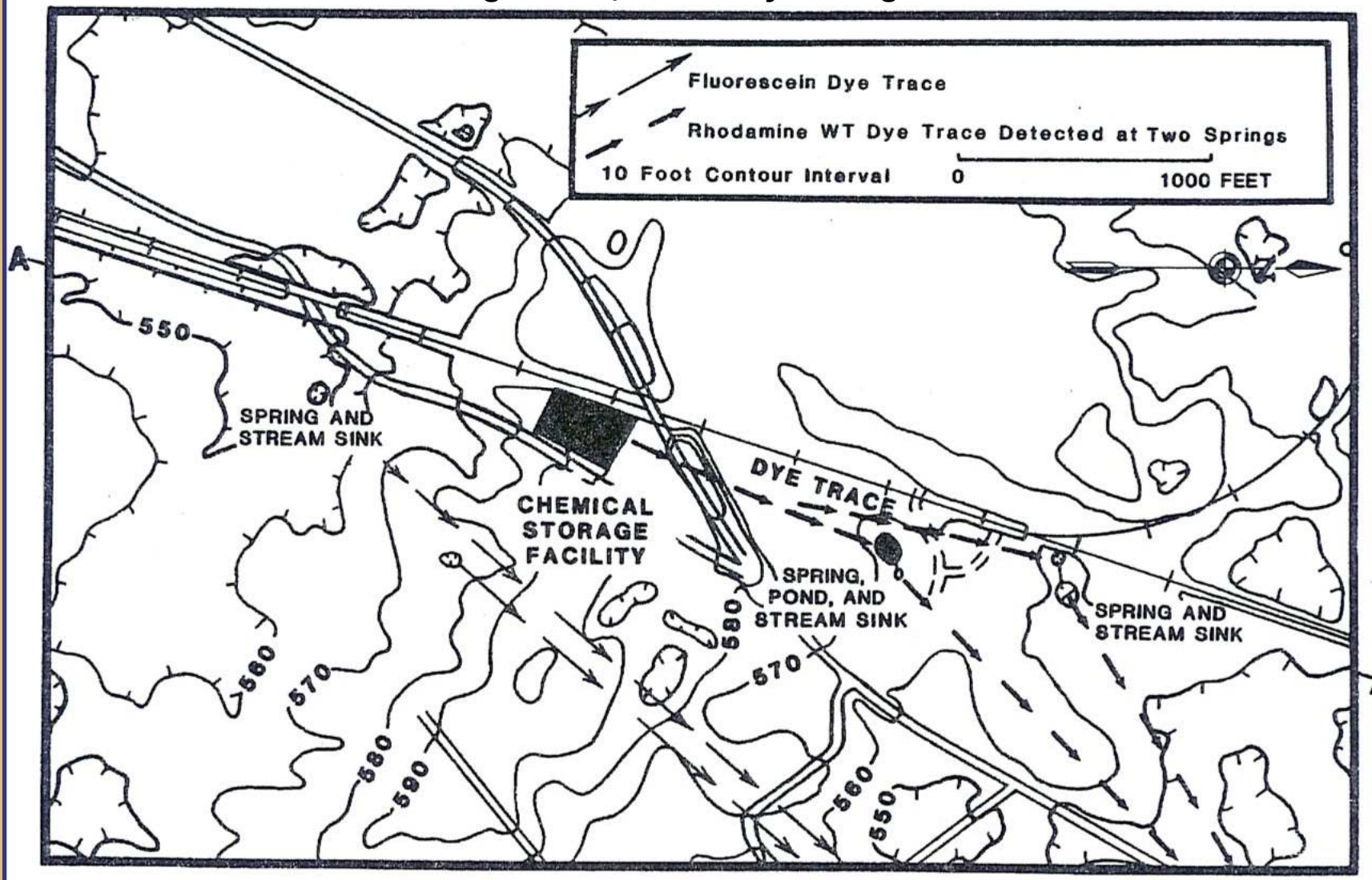


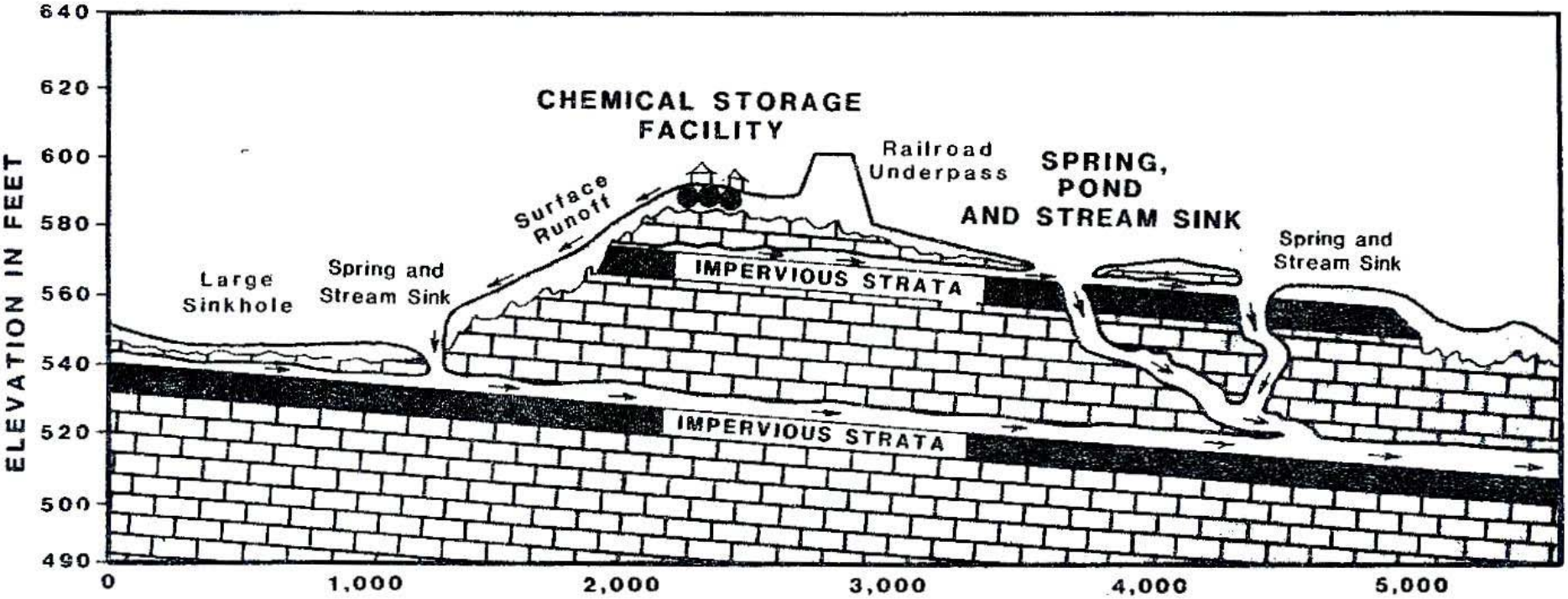
Change in discharge and water quality of Big Spring in response to a precipitation event. *Source: M. Ryan and J. Meiman* Ground Water, *34, no. 1 (1996):23 to 30.© Ground Water Publishing Company. Used with permission.*

The flux of
point source contaminants
through free-flow karst aquifers

KEITH POND SUPERFUND SITE

The flux of 12 toxic chemicals through the Lost River Cave System under Bowling Green, Kentucky during storm events





SITE CONCEPTUAL HYDROGEOLOGIC MODEL

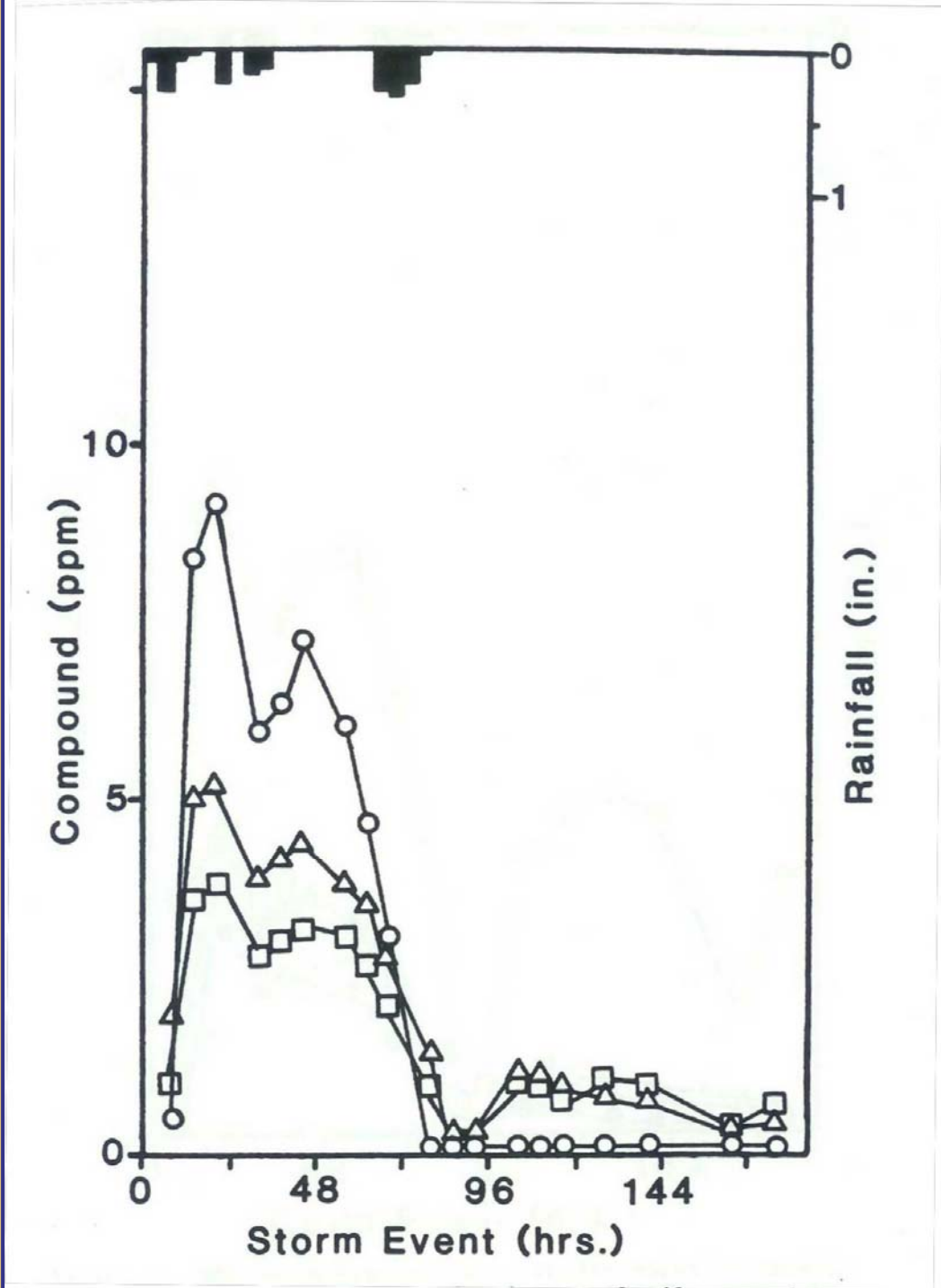
The concentration of primary volatile organic compounds at Keith Pond Spring - Sink during storm event one (December 18-25,1984).

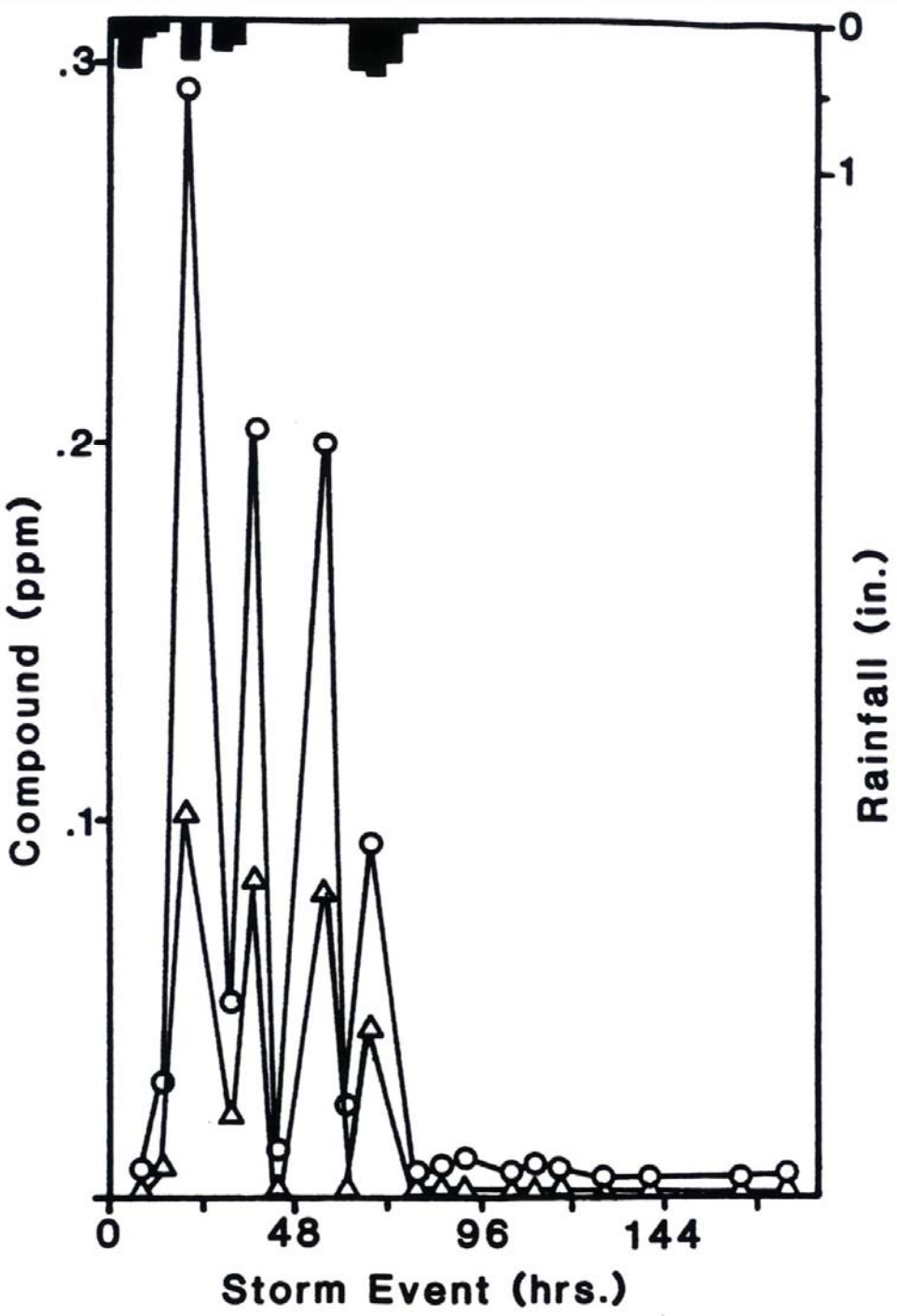
○ Toluene

△ 1,1,1-Tricholoroethane

□ trans-1,2-Dicholoroethylene

Source: Cretella, F. M. 1985, *A Priliminary Investigation of the Effect of Storm Events on the Concentration of Volatile Organic Compounds in the Lost River Cave System, Warren County, Kentucky.* M.S.Thesis, Western Kentucky University.



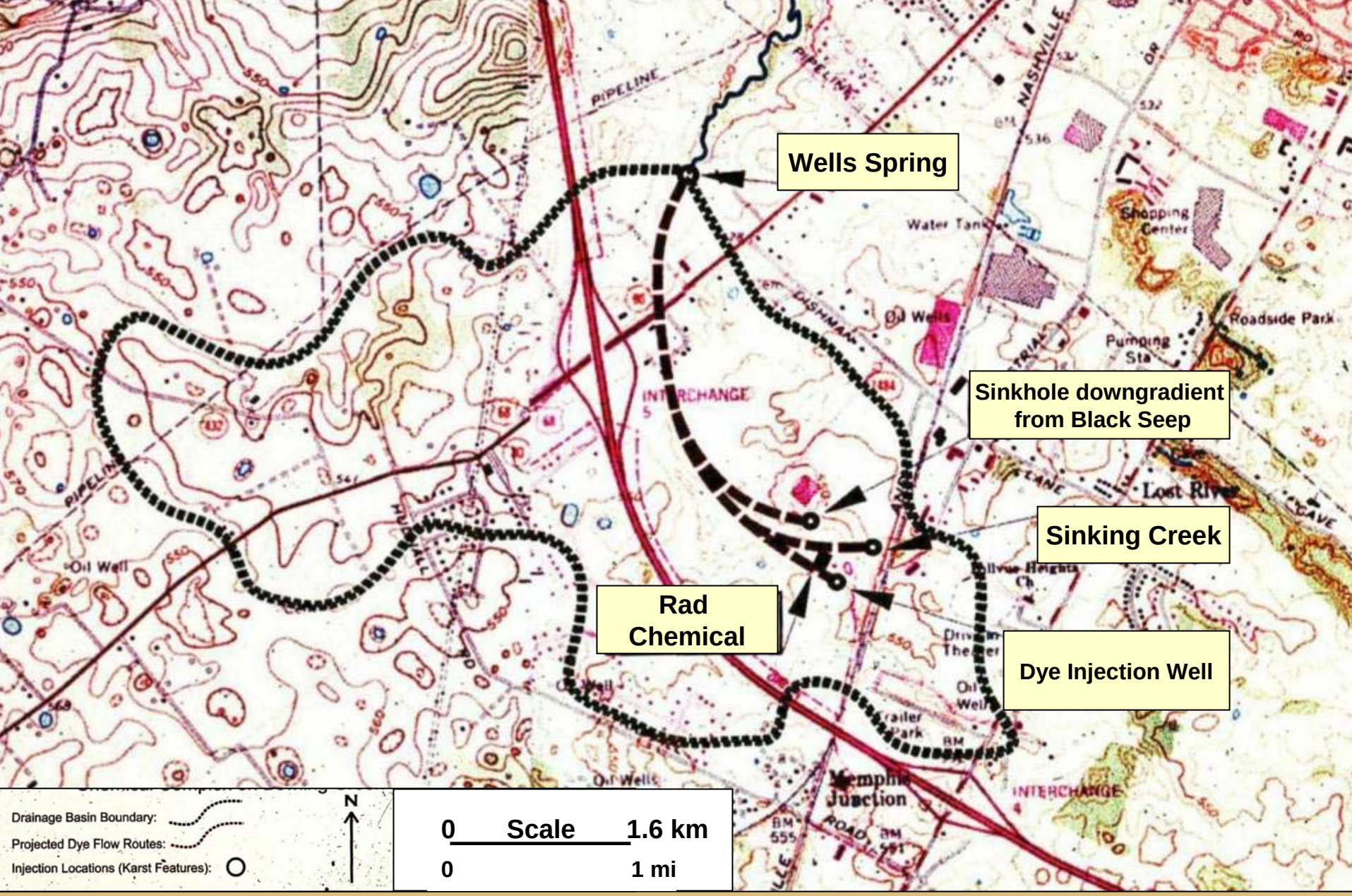


The concentration of primary volatile organic compounds at Lost River Blue Hole Spring – Sink during storm event one (December 18-25,1984).

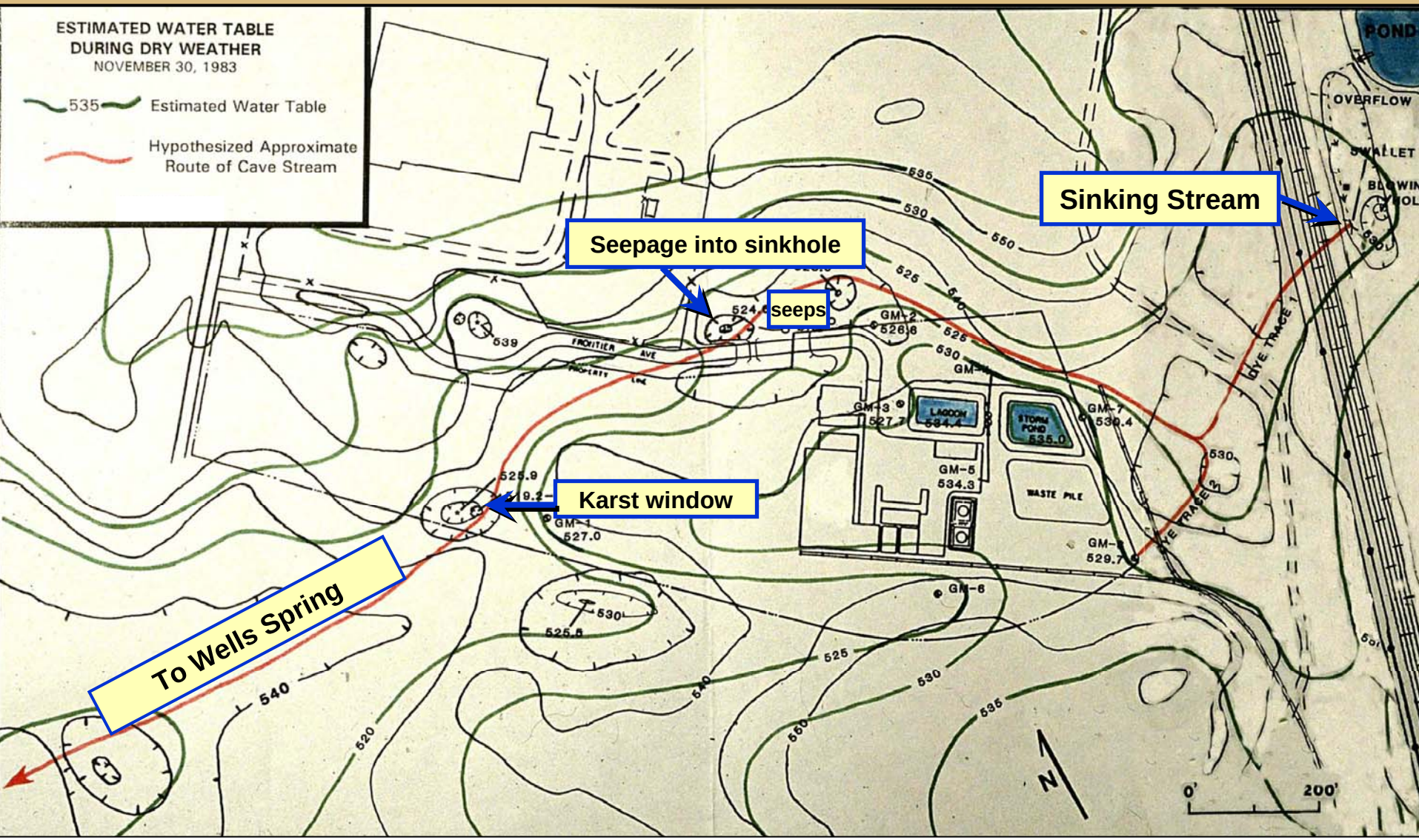
- ○ Toluene
- △ 1,1,1-Tricholoroethane
- □ trans-1,2-Dicholoroethylene

Source: Cretella, F. M. 1985, *A Priliminary Investigation of the Effect of Storm Events on the Concentration of Volatile Organic Compounds in the Lost River Cave System, Warren County, Kentucky.* M.S.Thesis, Western Kentucky University.

Storm Event Monitoring at Rad Chemical Superfund Site



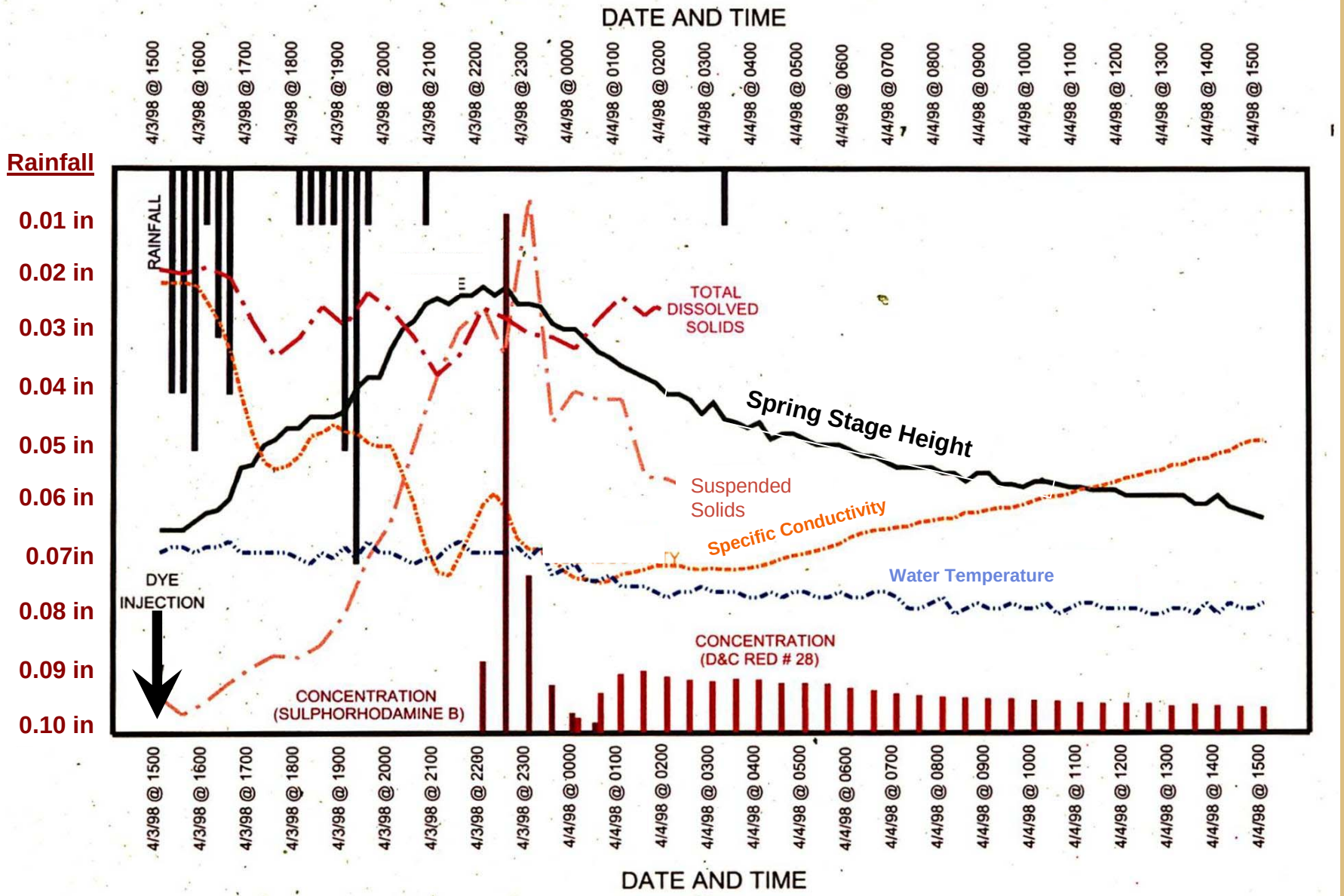
Dye traced groundwater flow from Rad Chemical Superfund Site to Wells Spring



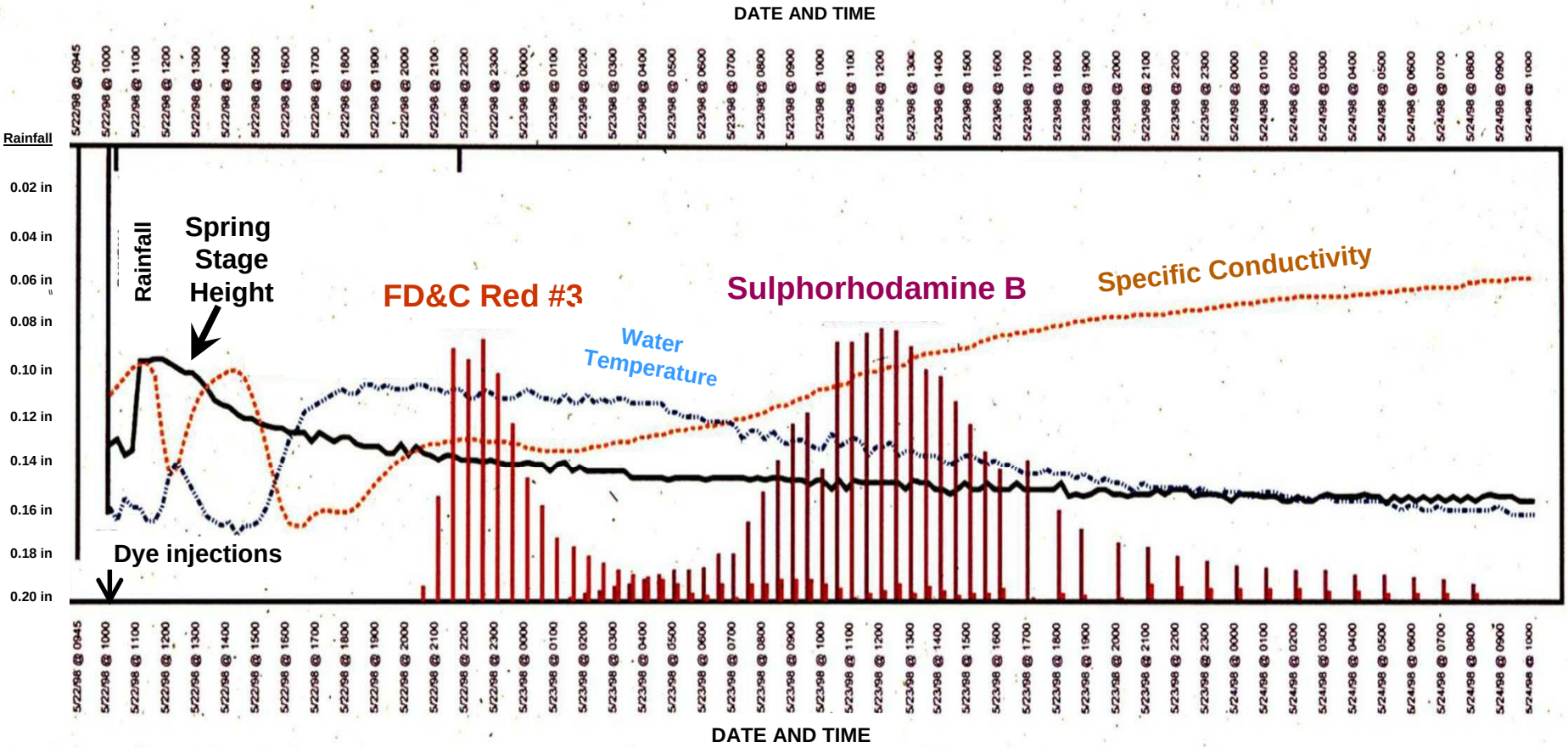
Water table contours and approximate location of cave stream as identified by dye tracer tests and microgravity.

Instrumentation at Wells Spring

DYE BREAKTHROUGH AND WATER QUALITY AT WELLS SPRING
TRACE ONE: 4/3/98 @ 1500 – 4/4/98 @ 1500



DYE BREAKTHROUGH AND WATER QUALITY AT WELLS SPRING
TRACE TWO: 5/22/98 @ 1000 – 5/24/98 @ 1000



Conclusions

Although non-point source and some point source contaminants are flushed through free-flow karst aquifers during storm events, the contaminant flux may not correlate with the spring discharge hydrograph due primarily to variation in rain events and source availability. Therefore, one cannot simply sample the peak during the storm discharge hydrograph, nor can one collect a discharge-proportional composite sample of the storm hydrograph.

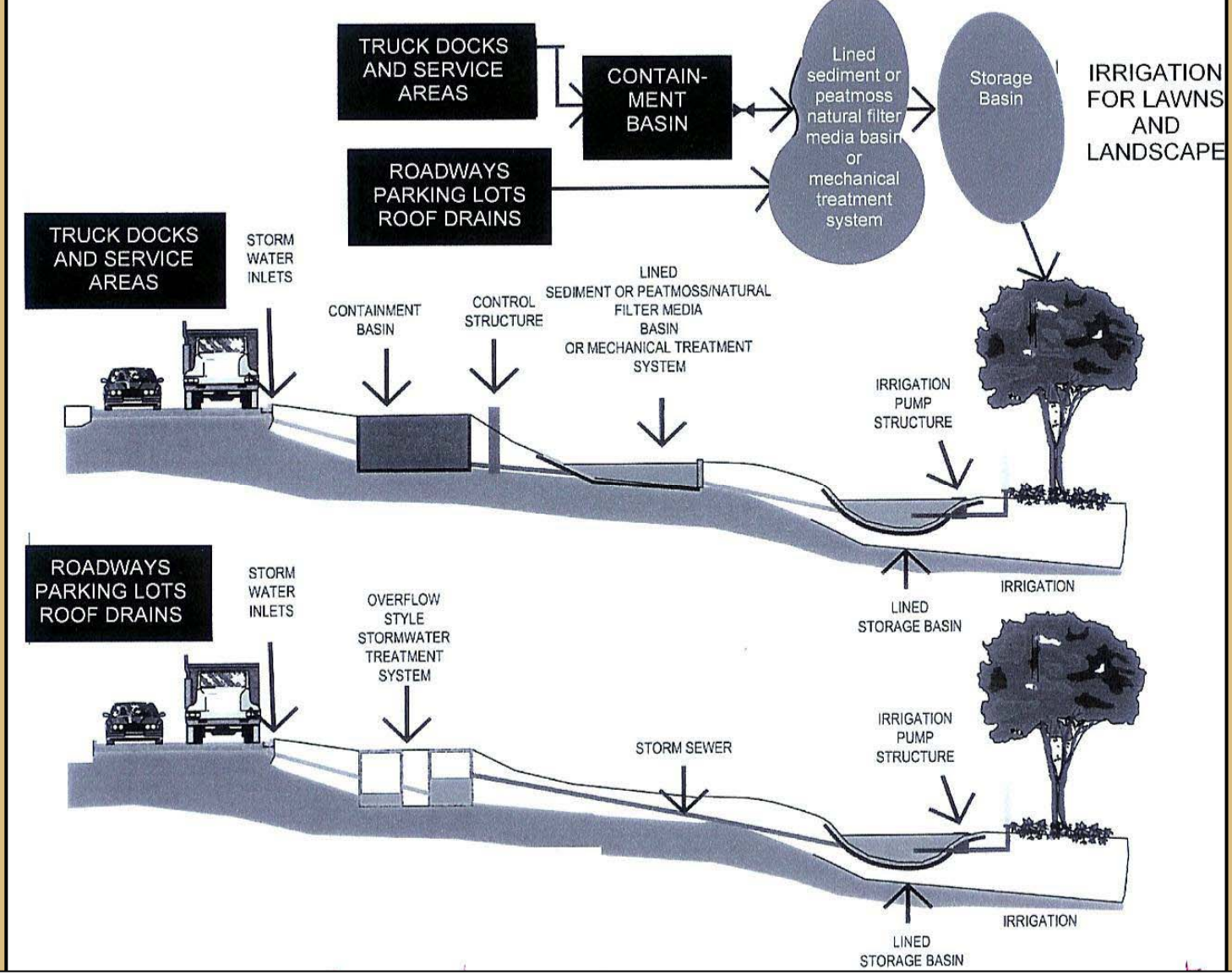
Recommendations

High-frequency, flow-dependent sampling during and after storm events combined with traditional long-term quarterly or monthly sampling are needed for monitoring both non-point and point source contaminants in free-flow karst aquifers.

Methods to Prevent Spills of Hazardous Liquids from Sinking into Karst Aquifers

Requirements at the new Kentucky Trimodal Transpark, Bowling Green, Kentucky:

1. Storage of large quantities of hazardous liquids not permitted.
2. Tertiary containment for underground tanks required.
3. Collection system for surface spills of hazardous liquids included with the required storm water management system.



Required storm water runoff system for Transpark. Designed to: 1) provide tertiary treatment of storm water runoff, 2) contain spills of hazardous chemicals, 3) prevent sinkhole flooding, and 4) prevent storm water induced regolith collapse sinkholes. Design by: Mayes, Sudderth, and Etheredge, Inc.


11/22/2033


11/22/2033


EAST JORDAN IRON WORKS
Vortechnics
VORTECHS
STORMWATER
TREATMENT
MADE IN USA
11/22/2033


11/22/2033


11/22/2033


11/22/2033


11/22/2033


11/22/2033


11/22/2033


NO
TRESPASSING
11/22/2033


11/22/2033

MICROGRAVITY AND ELECTRICAL RESISTIVITY TECHNIQUES FOR KARST SUBSURFACE INVESTIGATIONS

DENSITY ASSUMPTIONS

Air = 0g/cm^3

Water = 1.0 g/cm^3

Cave sediments or regolith = 1.5-2.21 g/cm^3

Limestone = ~2.67 g/cm^3

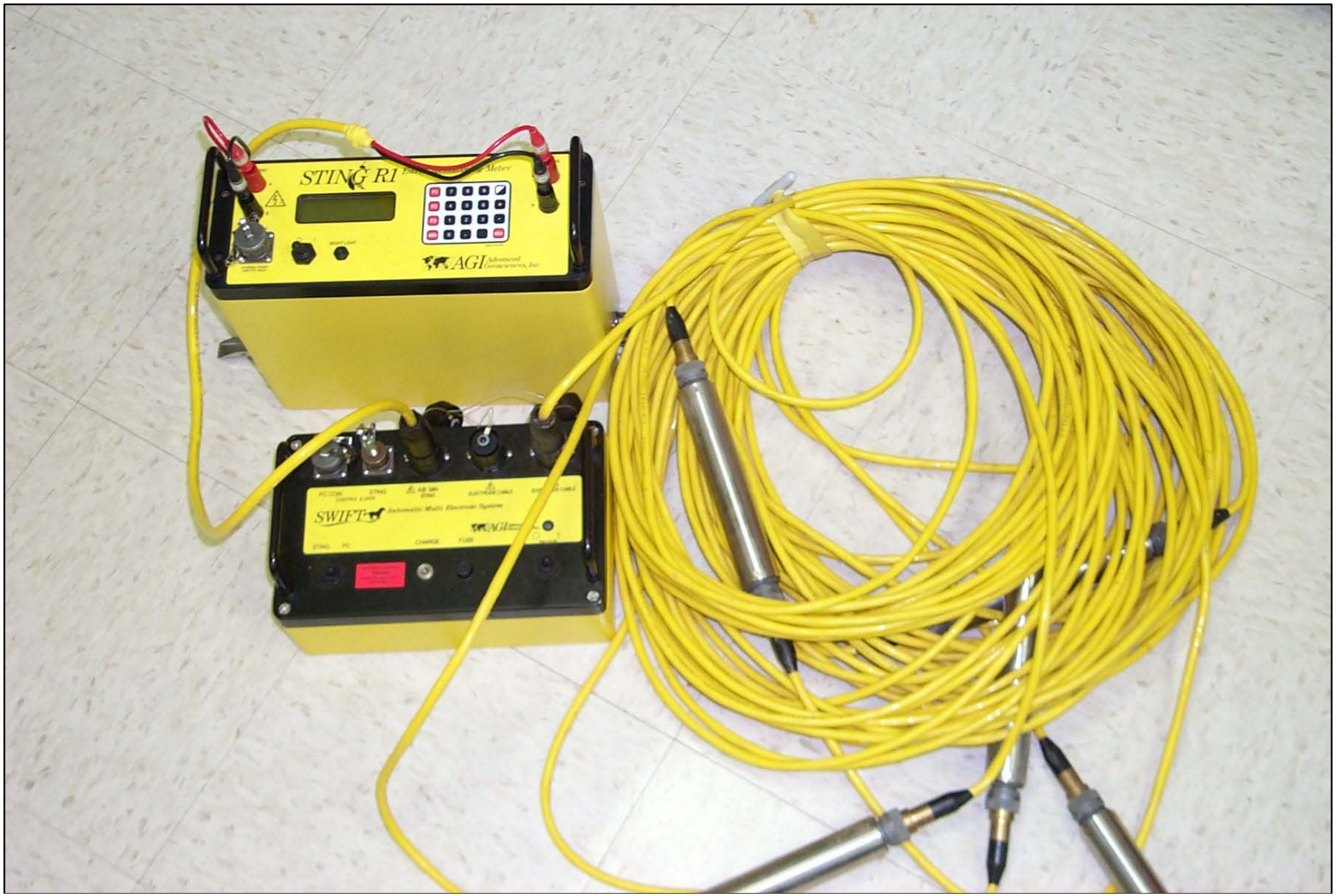
Therefore,

Air-filled cave or tunnel in limestone bedrock equals a density contrast of ~2.67 g/cm^3

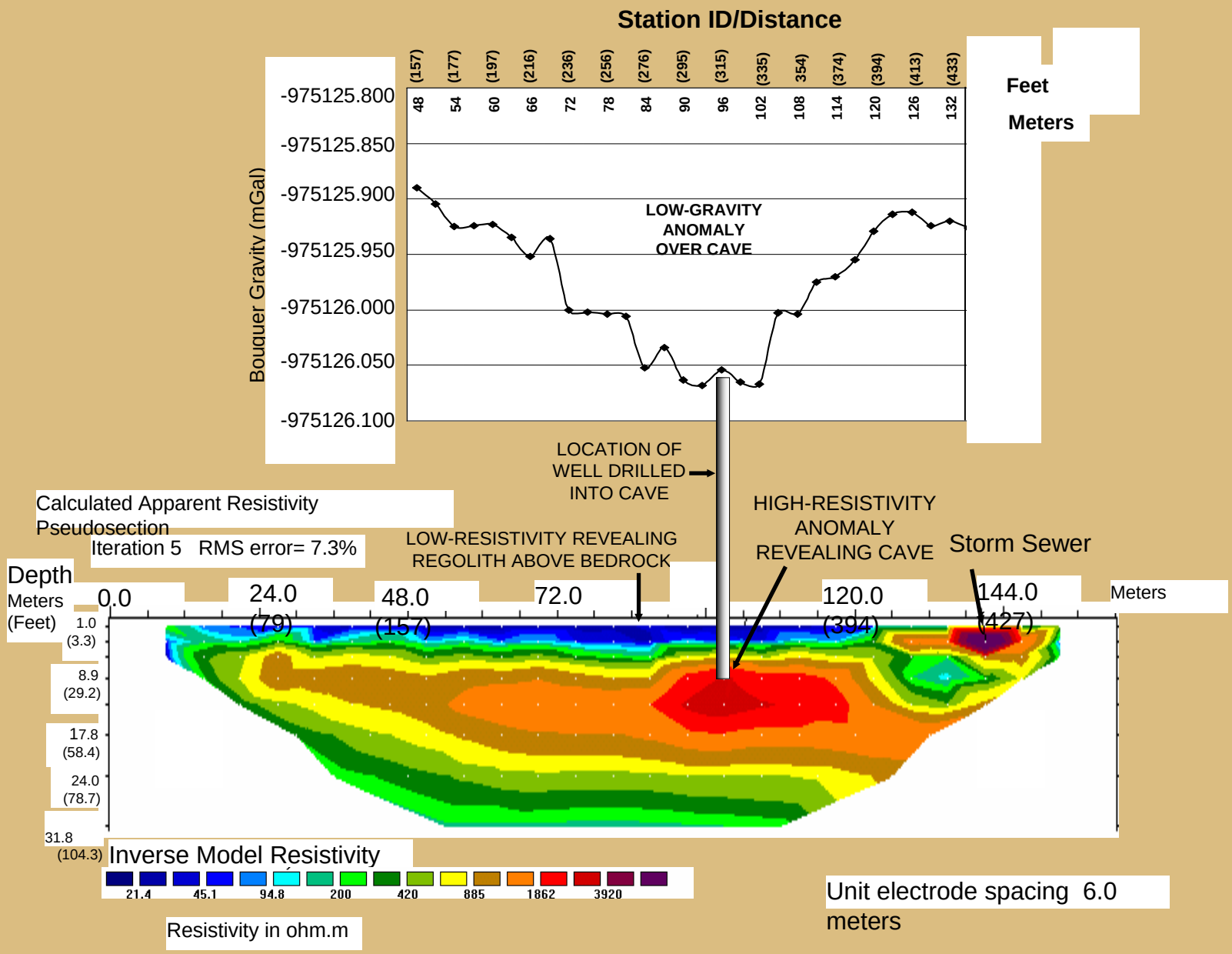
Air-filled void or tunnel in regolith (unconsolidated material above bedrock) equals a density contrast of 1.5-2.21 g/cm^3

LaCoste and Romberg Model D Microgravity Meter

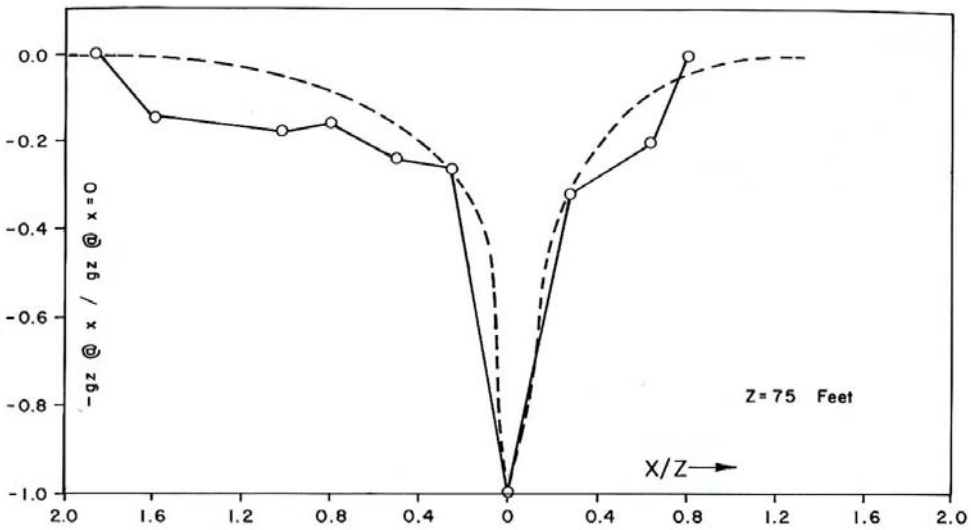
Scintrex CG-3M
Autograv
Microgravity Meter

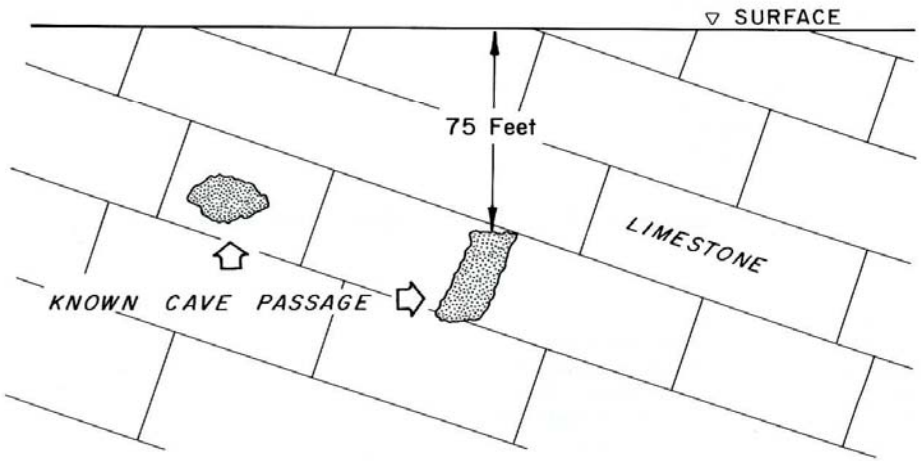


Sting / Swift Electrical Resistivity Meter



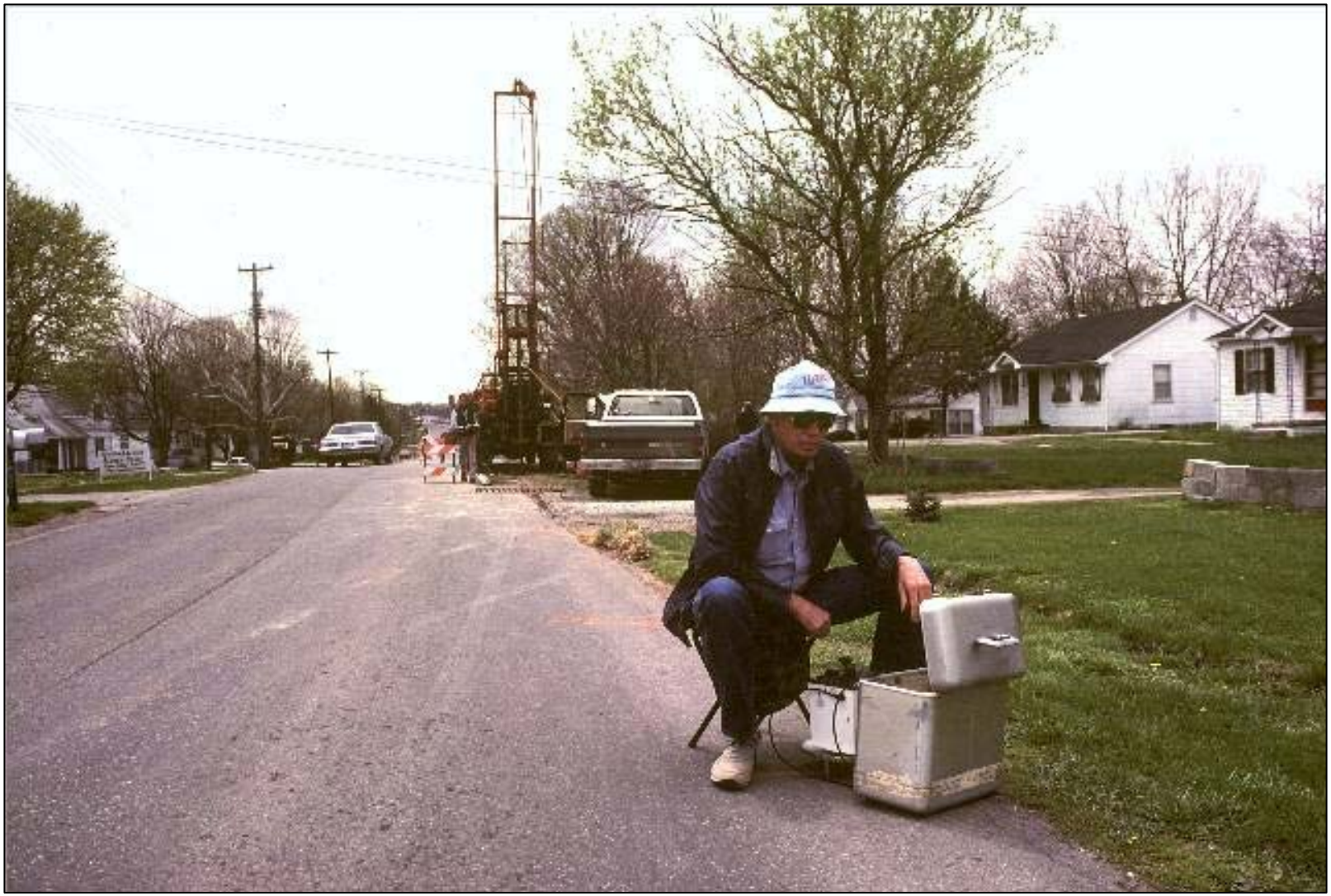
Low-gravity and high-resistivity anomalies reveal previously unknown cave.



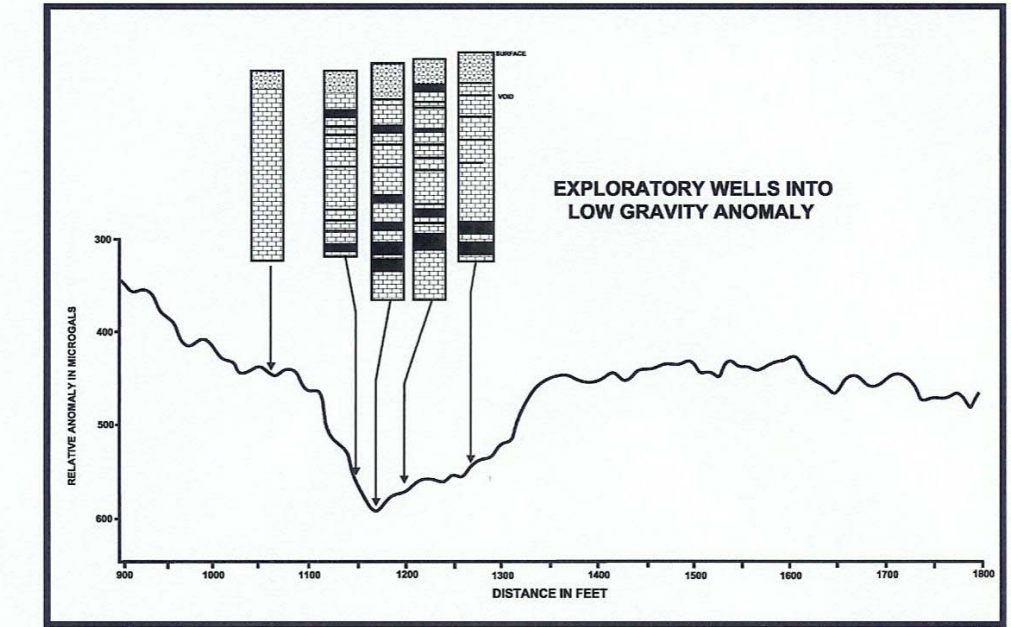


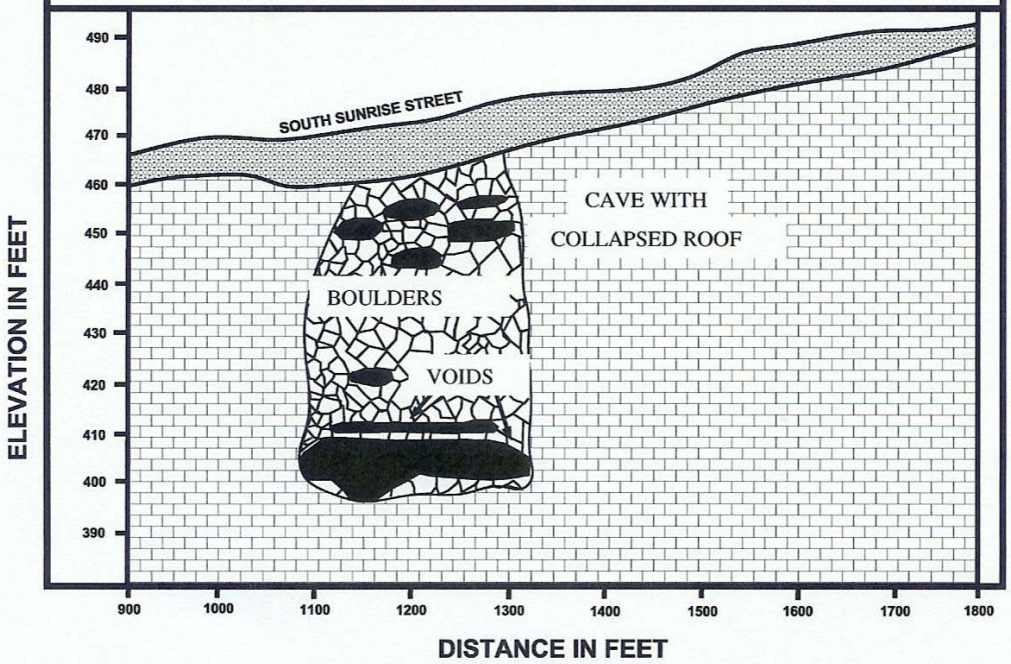
Detection of Fletcher Cave using a gravity meter

(from Kirk, 1974)

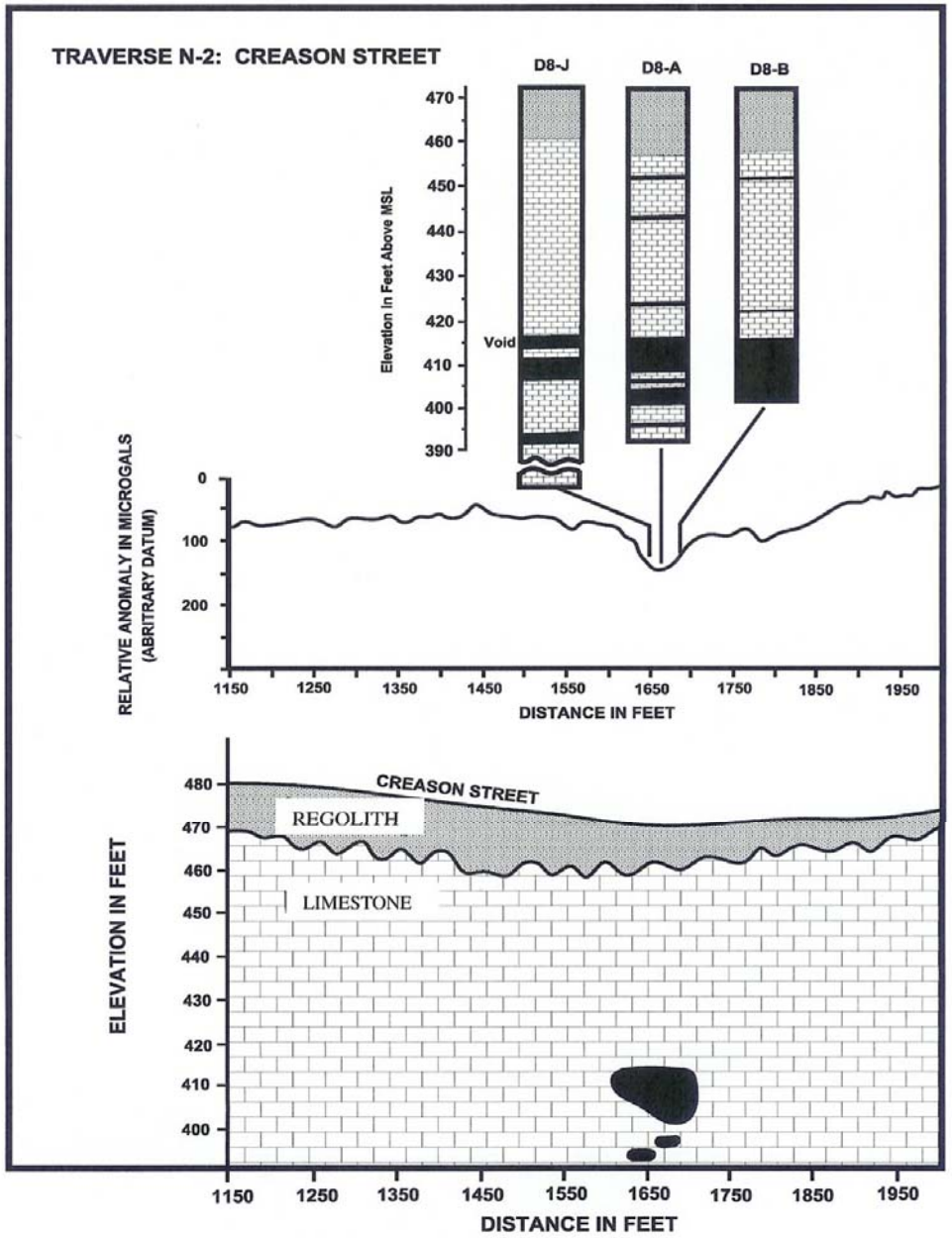


First attempt to explore for unknown caves. LaCoste and Romberg Model D microgravity meter.



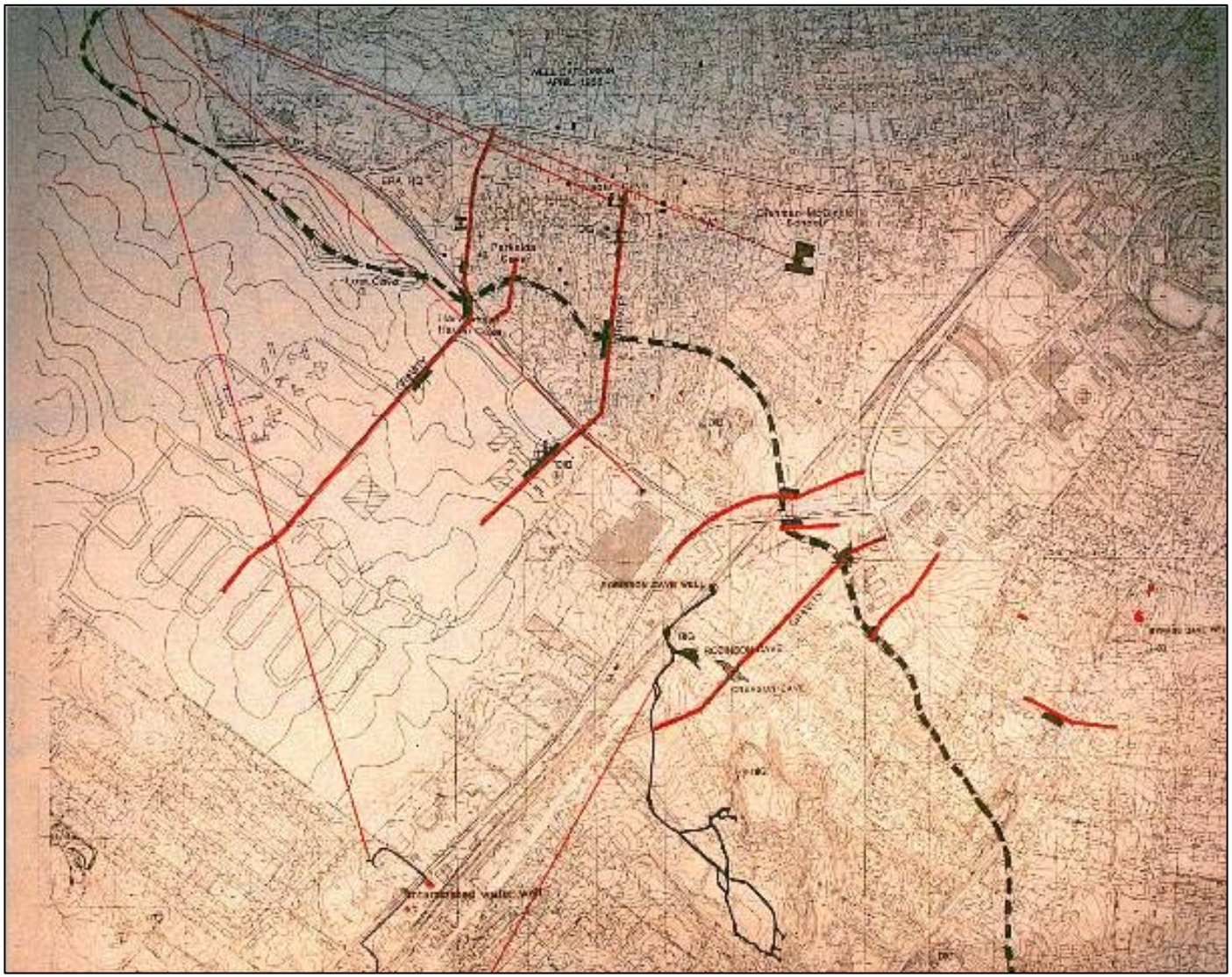


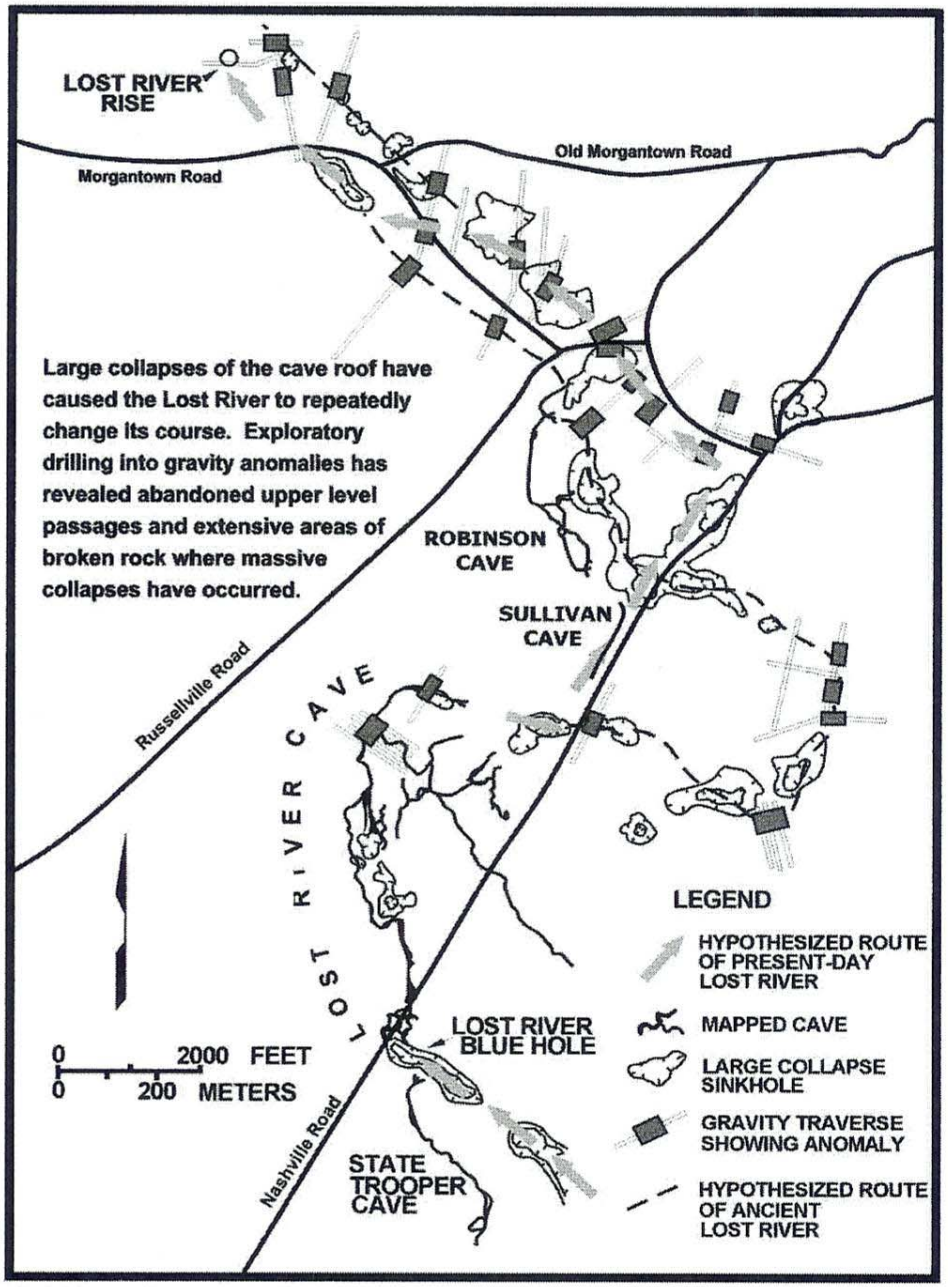
First cave detected by microgravity. Wells were cored into both low-gravity anomaly and outside of anomaly to confirm detection.



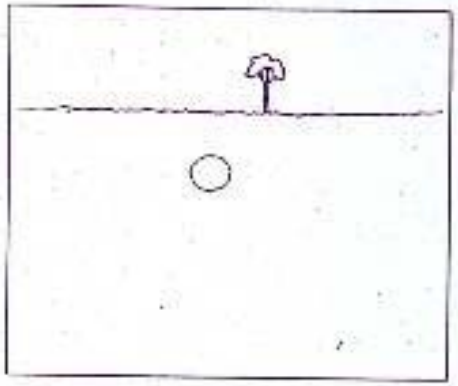
Wells drilled into this low-gravity anomaly revealed Lost River Cave under Creason Street in Bowling Green, Kentucky.

Microgravity traverses perpendicular to hypothesized route of Lost River Cave revealed low-gravity anomalies that were then drilled and confirmed by dye tracer tests to be the Lost River flowing under Bowling Green.

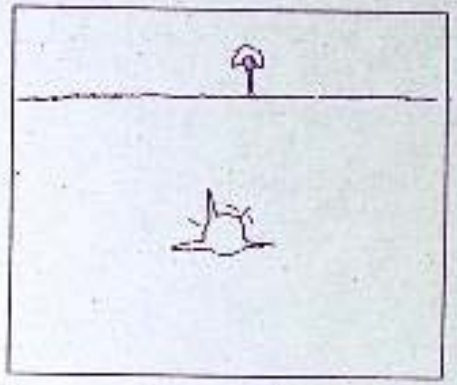




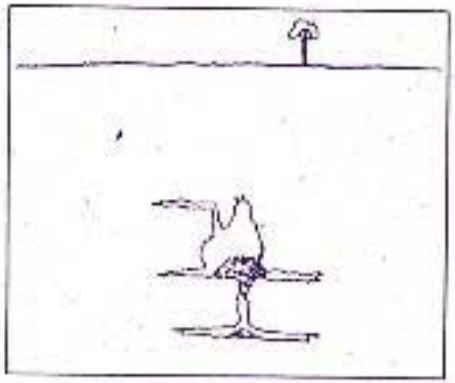
Mapped portions of Lost River Cave and present-day and ancient routes as determined by microgravity (Crawford, 1986). Notice that some of the low-gravity anomalies are over previously mapped portions of Lost River Cave. Most of the other low-gravity anomalies have been confirmed by exploratory borings into the low-gravity anomaly and along both sides of the anomaly. Dye tracer tests were performed to confirm that the wells drilled into the low-gravity anomalies were in fact the Lost River.



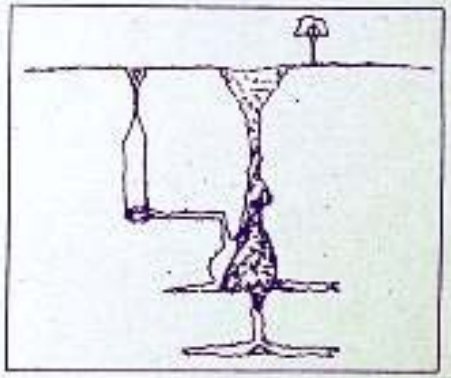
A spherical cavity can be theoretically detected at a maximum depth of a few times its diameter.



Halo effect allows most cavities to be detected deeper.



Most cavities are part of a complex cave system and can be detected at even greater depths.

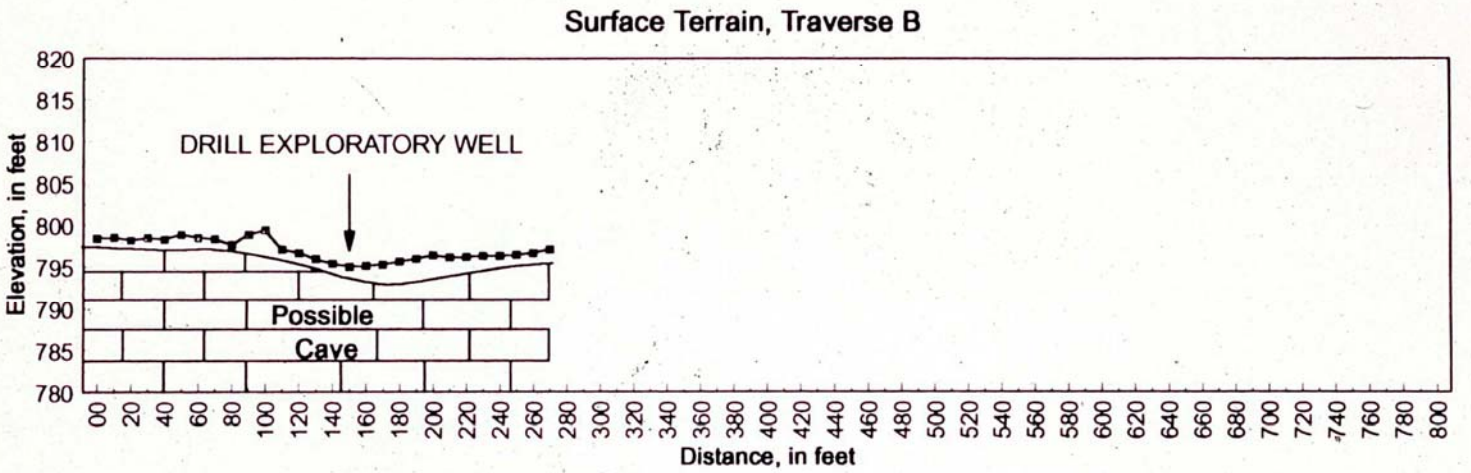


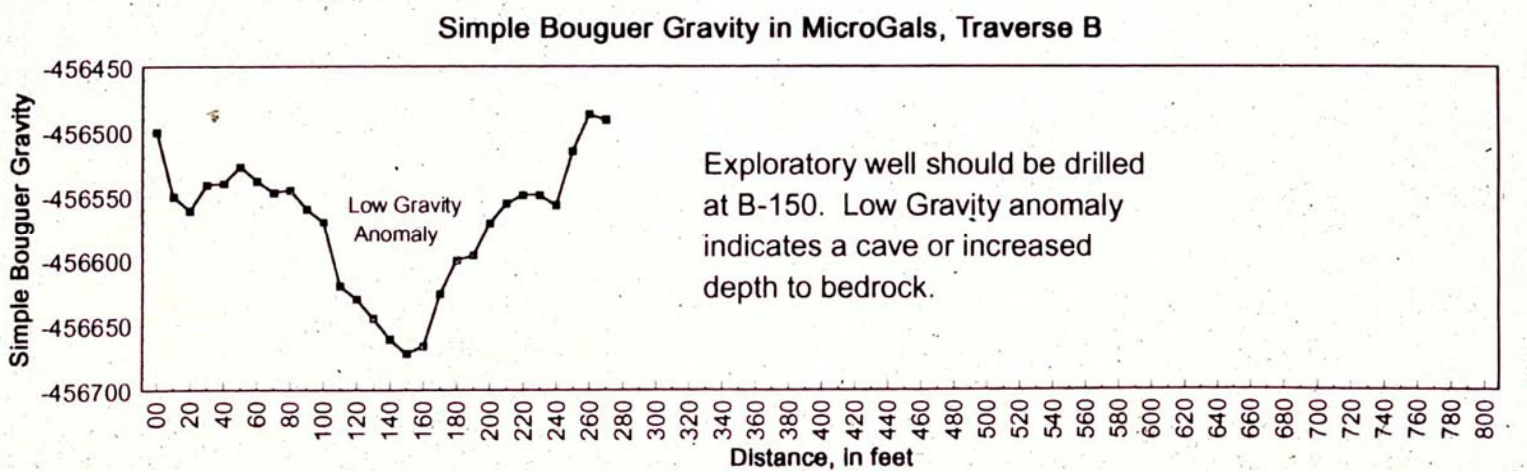
Near surface indicators often allow cavity systems to be detected beyond the range and resolution of most geophysical methods.

From Benson and Yuhr, 1993

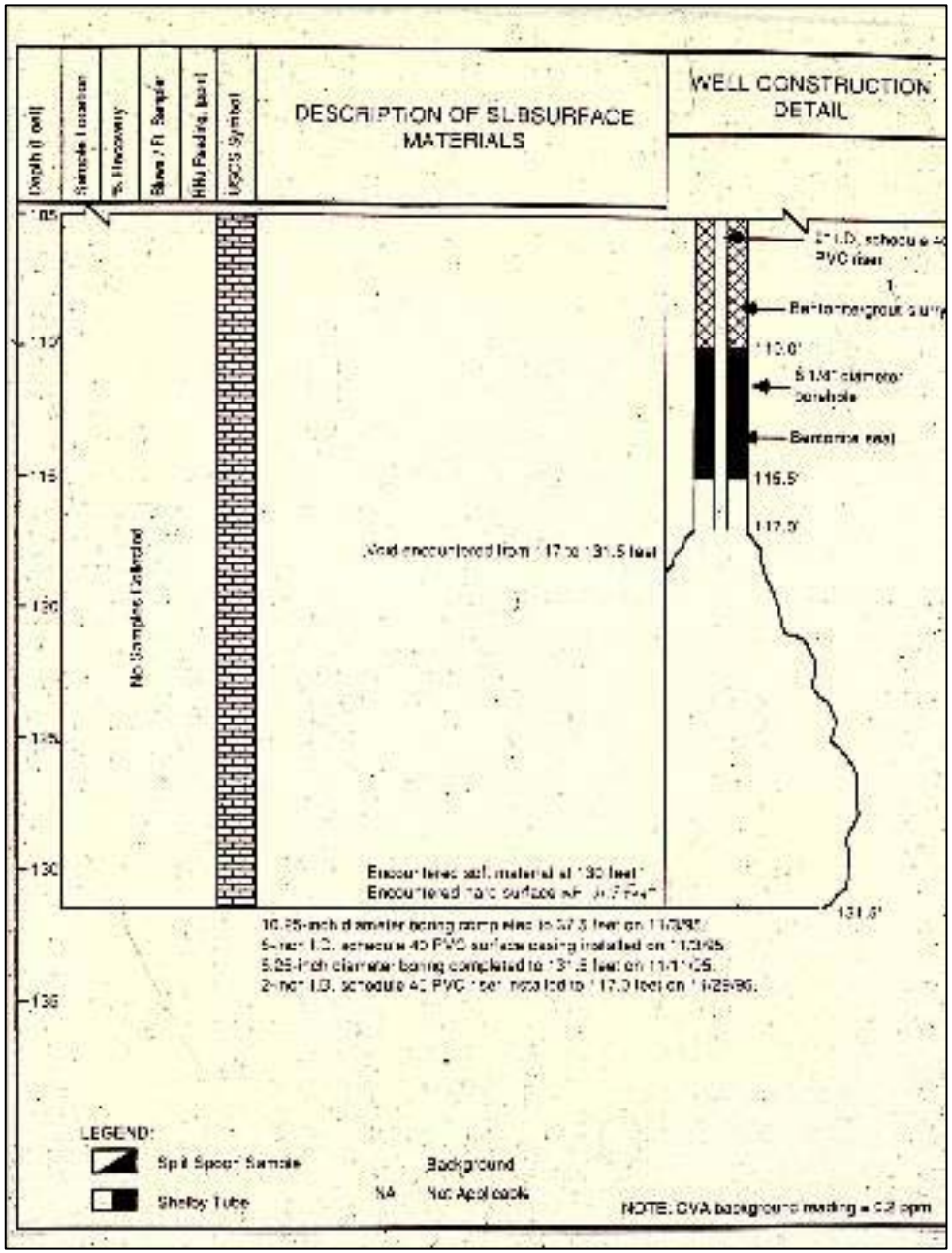
Halo effect permits detection of caves at a lower depth than would be the case for a spherical cavity.

American Wire Microgravity Survey
Frankfort,Kentucky

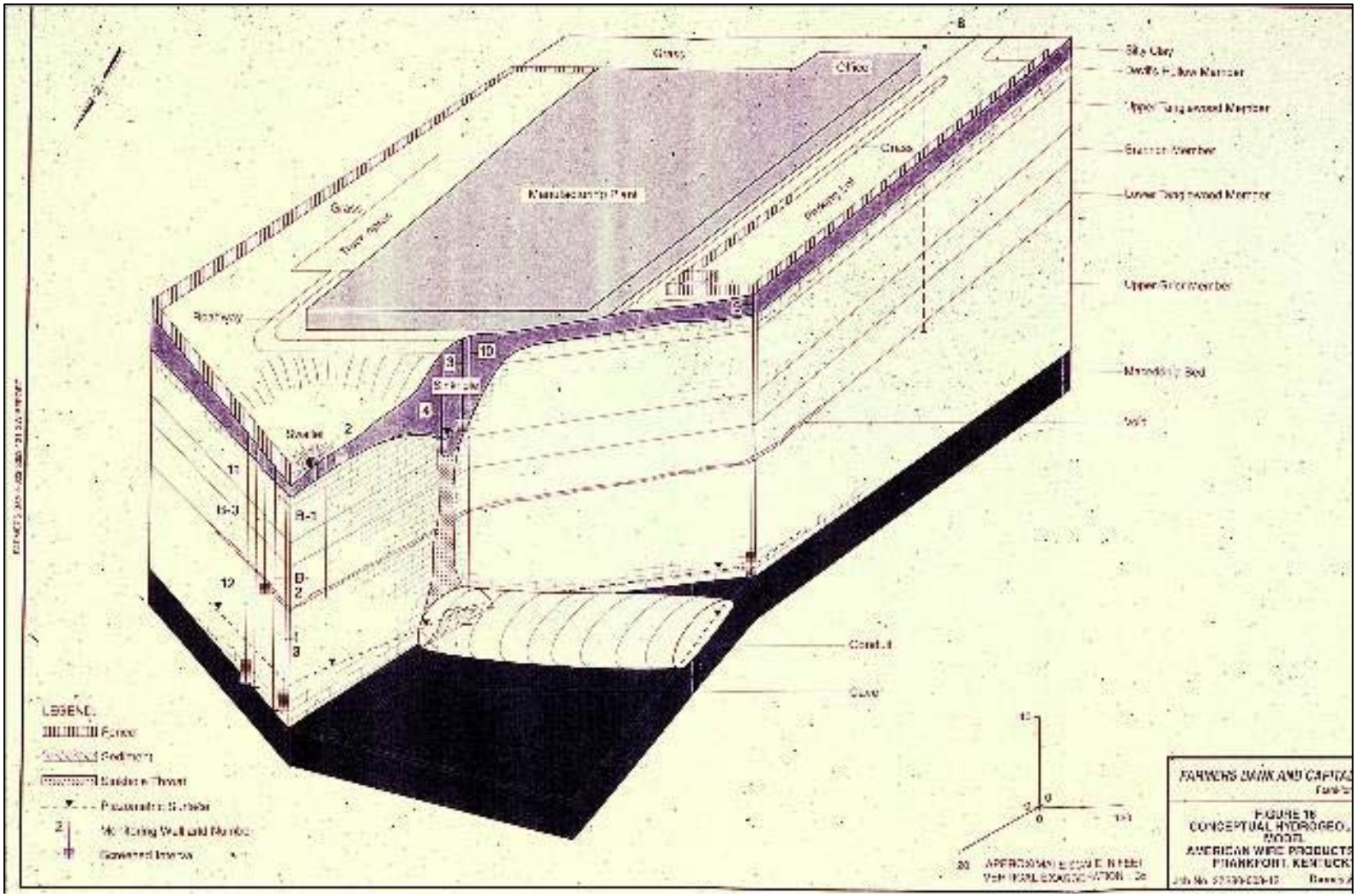




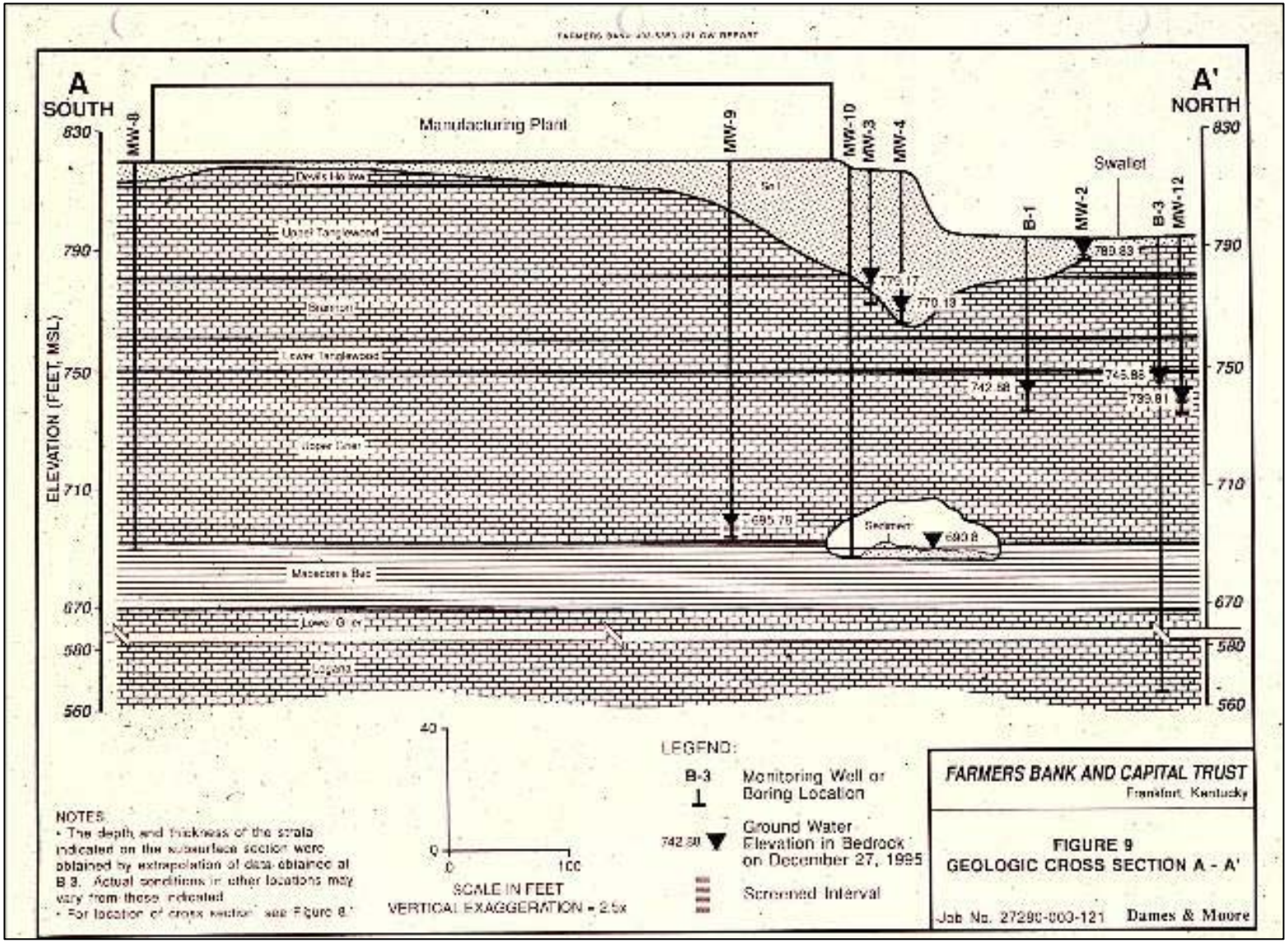
Exploratory well should be drilled at B-150. Low Gravity anomaly indicates a cave or increased depth to bedrock.



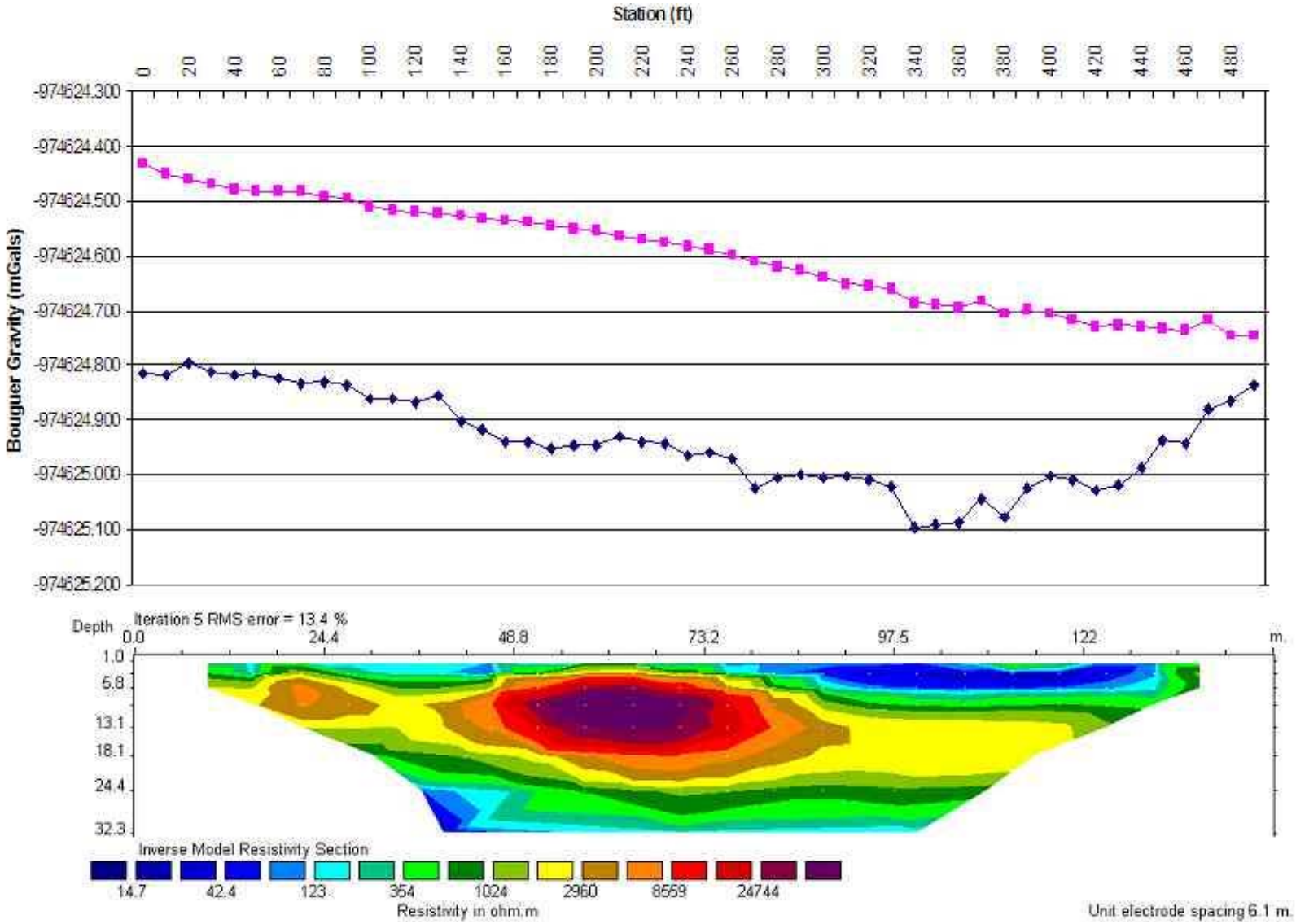
Exploratory boring into low-gravity anomaly on the American Wire property revealed a cave and cave stream at a depth of 117 feet. The well permitted groundwater monitoring for the site.



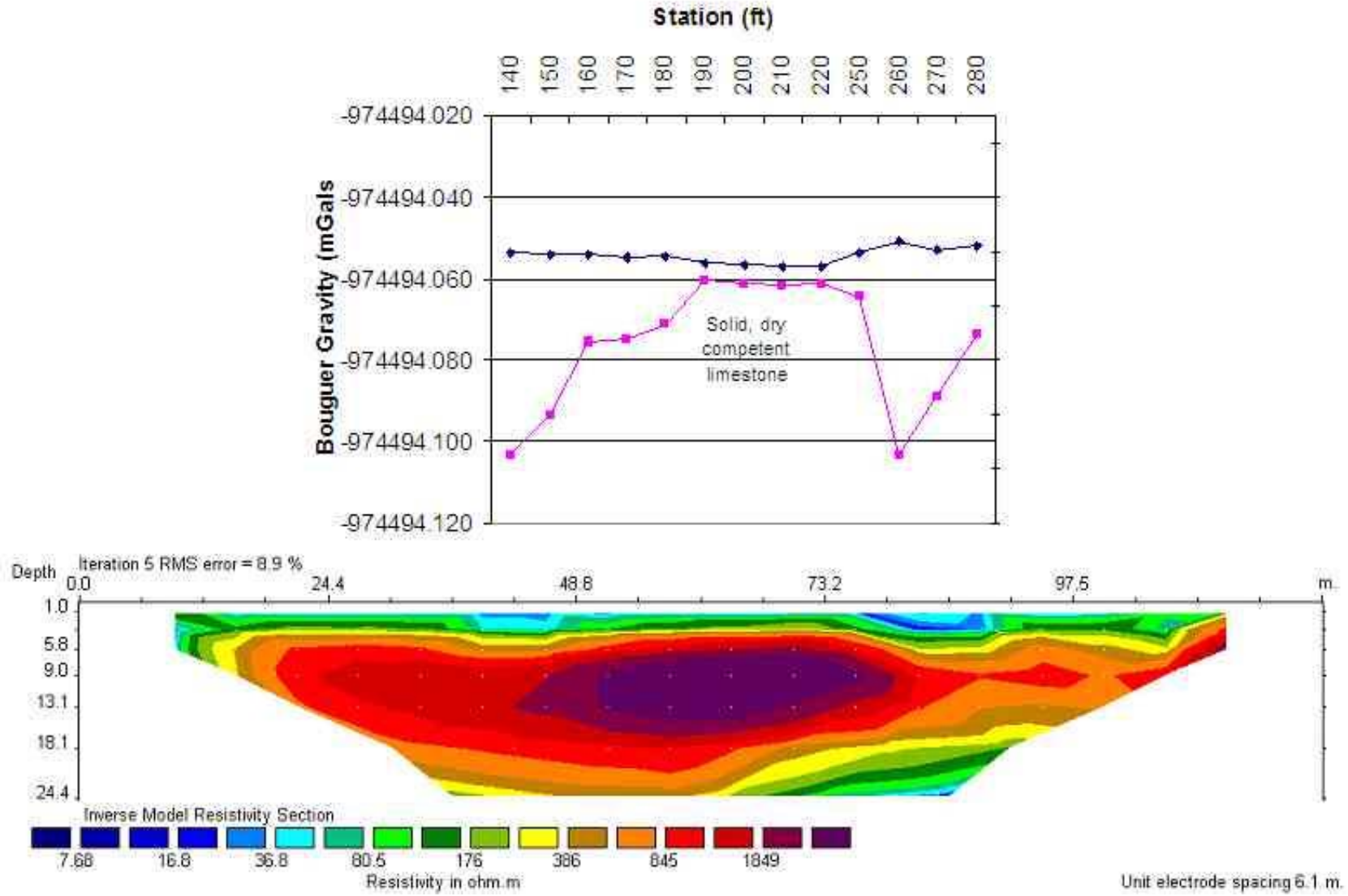
American Wire well drilled into cave passage at a depth of 117 feet.



Other wells drilled in the vicinity of American Wire did not intersect the cave passage.



Pockets of dry solid limestone often resemble caves. Microgravity is virtually always needed to confirm that a high-resistivity anomaly is a cave.



Pockets of dry solid limestone often resemble caves. Microgravity is virtually always needed to confirm that a high-resistivity anomaly is a cave.

Center for Cave and Karst Studies Dye Tracer Test Information:

dyetracing.com

&

caveandkarst.wku.edu